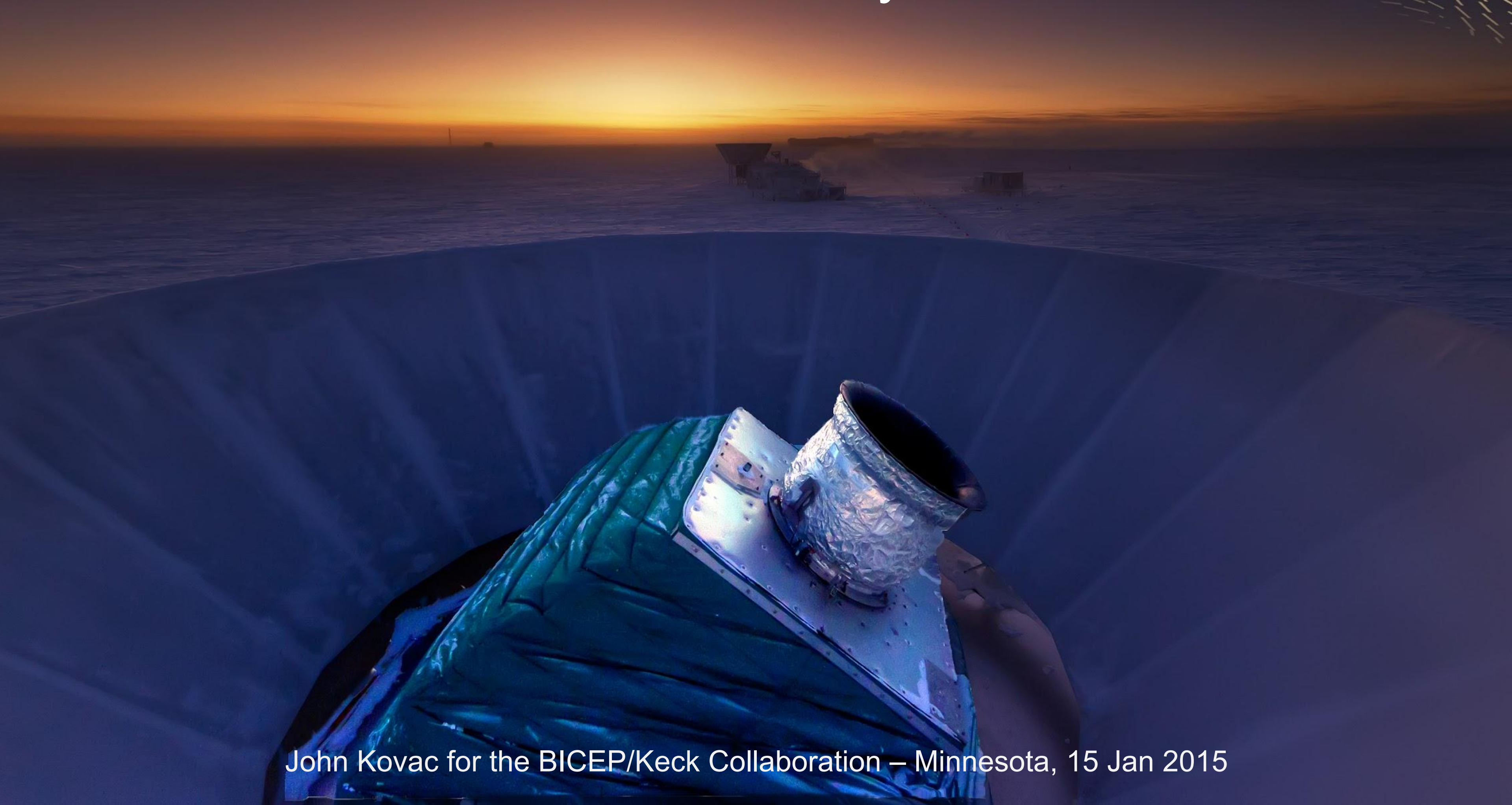
B-mode Polarization Results

from the BICEP / Keck Array series and status of Keck Array and BICEP3



John Kovac for the BICEP/Keck Collaboration – Minnesota, 15 Jan 2015


VE RI TAS
HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
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JPL
NIST
CARDIFF
UNIVERSITY
cea
UNIVERSITY OF
TORONTO
UBC

+BICEP3

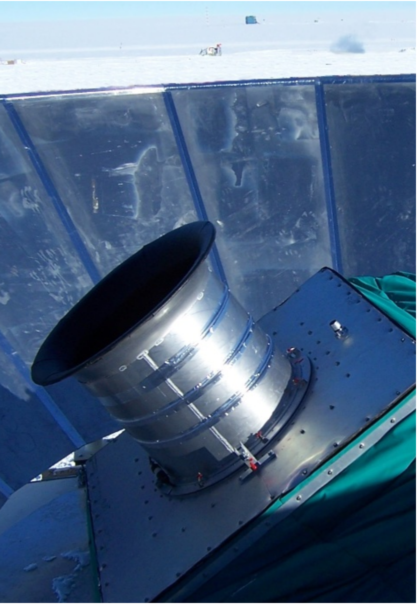
BICEP2/Keck

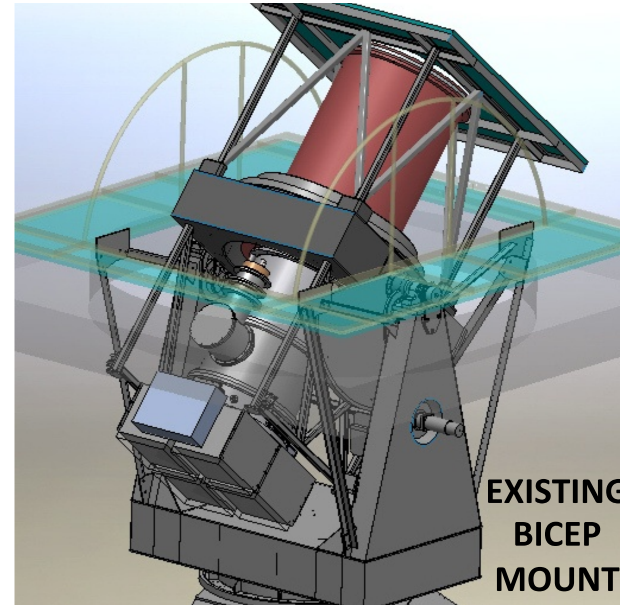
launching Cosmology's greatest wild goose chase

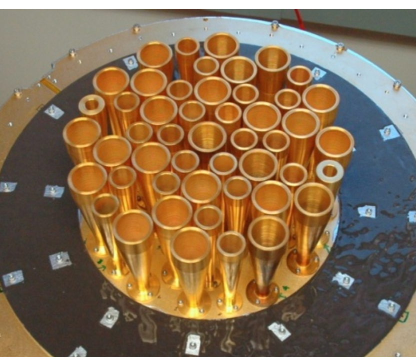
The Search for Inflationary B-Modes

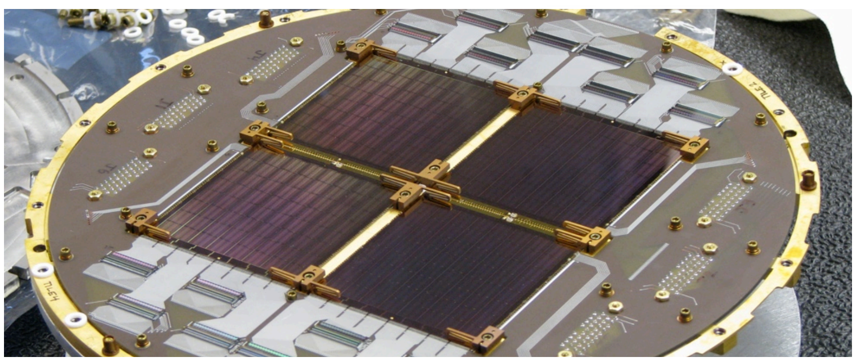
Andrew Lange
Caltech Marvin L. Goldberger Professor of Physics
1957 - 2010

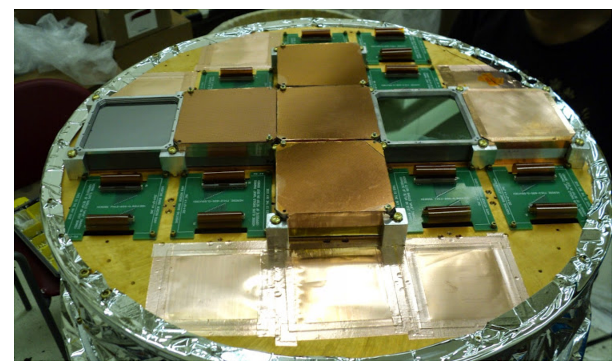
BICEP (2006–2008) BICEP2 (2010–2012) KeckArray (2011–) BICEP3 (2015-)











98 NTDs (95/150 GHz)	512 TESs (150 GHz)	2560 TESs (150 GHz)	2560 TESs (95 GHz)
0.93°/0.60° FWHM	0.52° FWHM		0.37° FWHM
18° FOV	17° FOV		26° FOV
44 m^2 deg^2 AΩ	44 m^2 deg^2 AΩ	222 m^2 deg^2 AΩ	502 m^2 deg^2 AΩ optical throughput

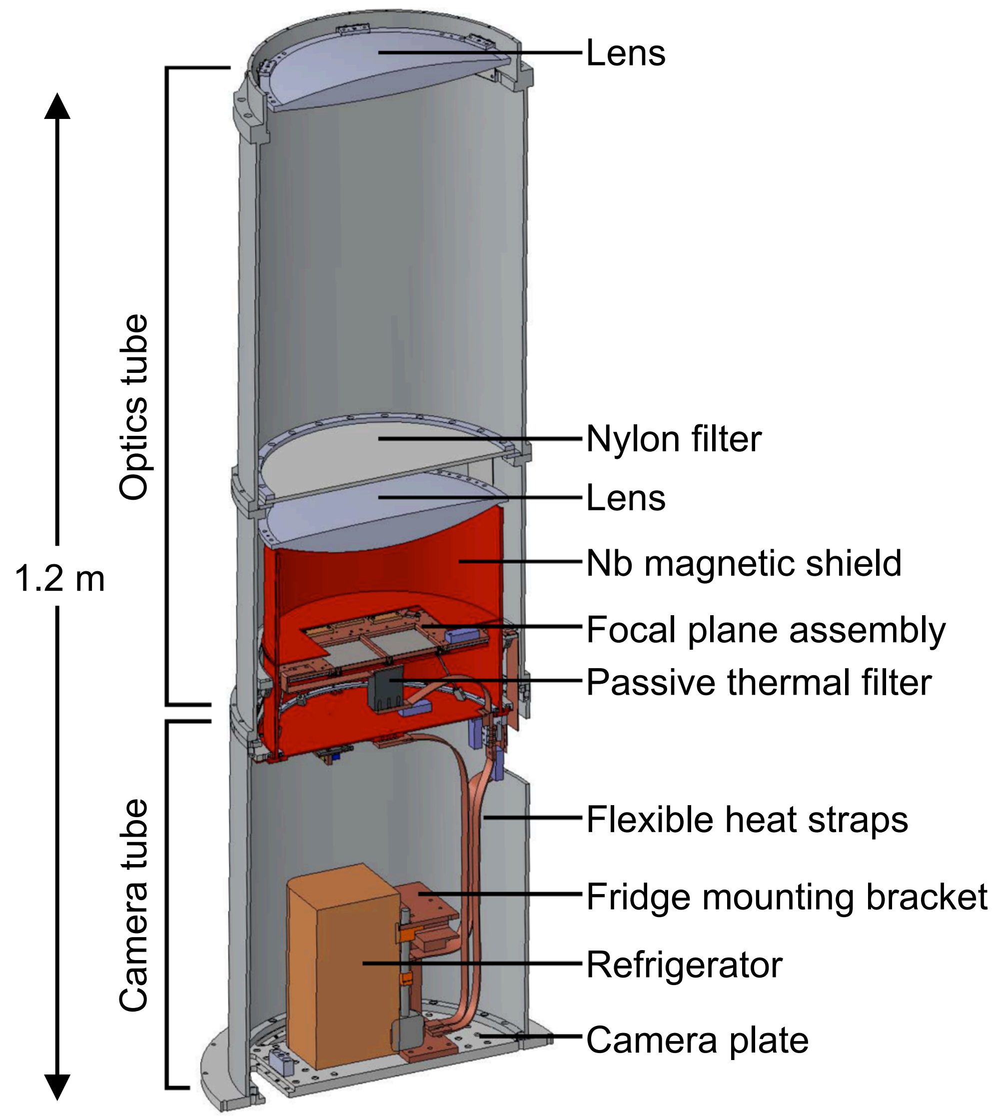
The BICEP2/Keck Telescopes

Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

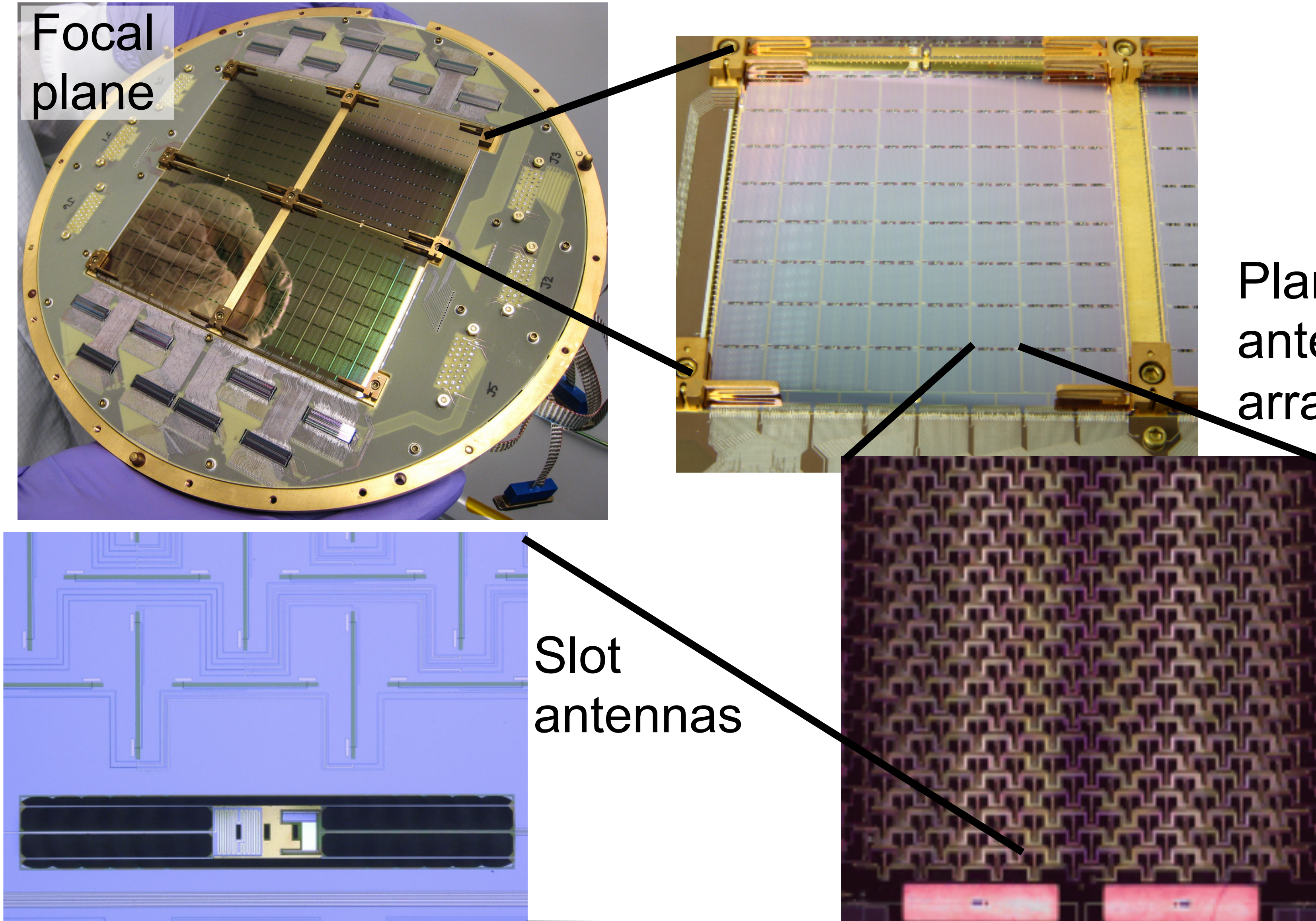
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Liquid helium (or PT cooler) cools the optical elements to 4.2 K.

A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.

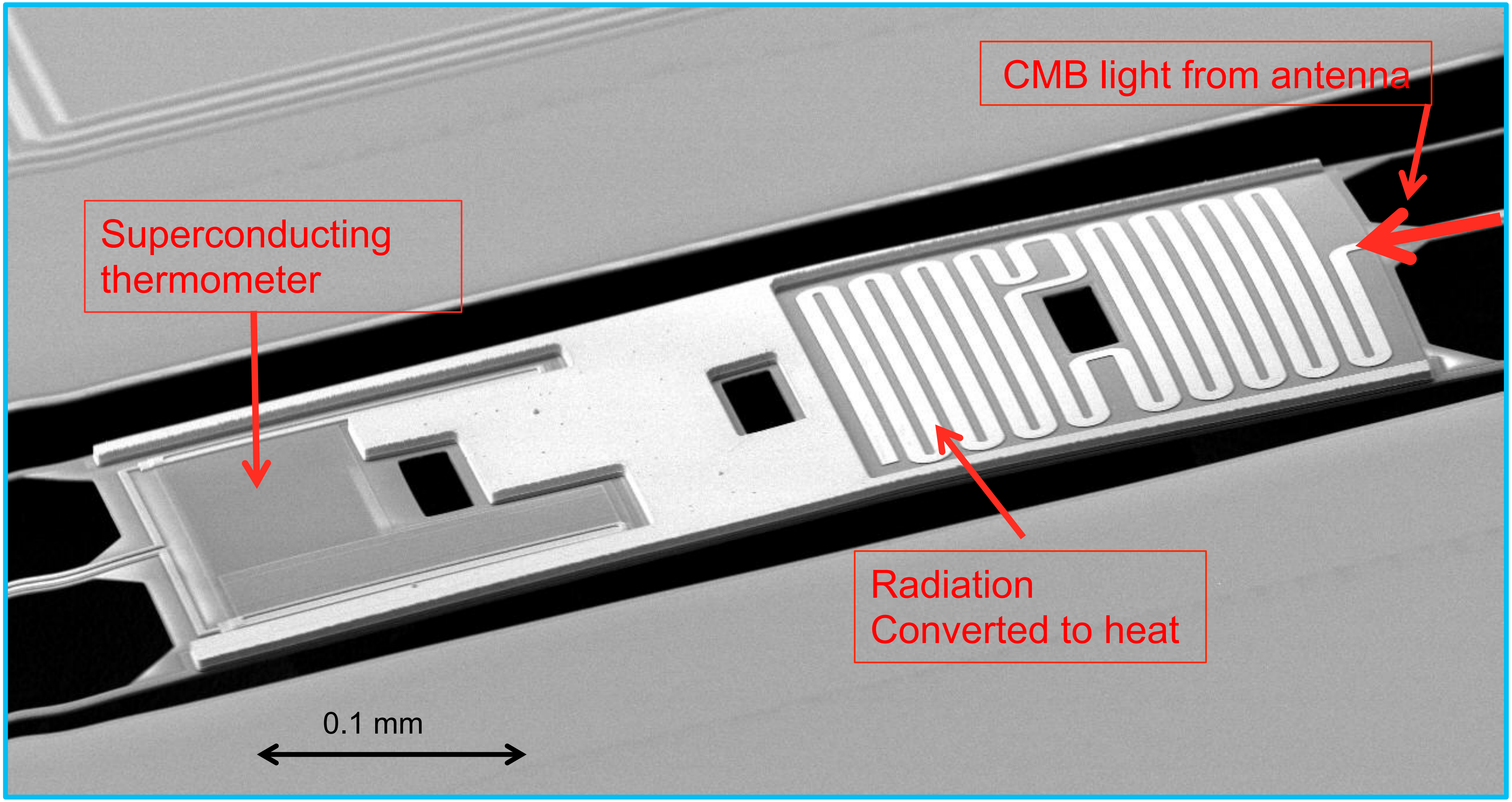


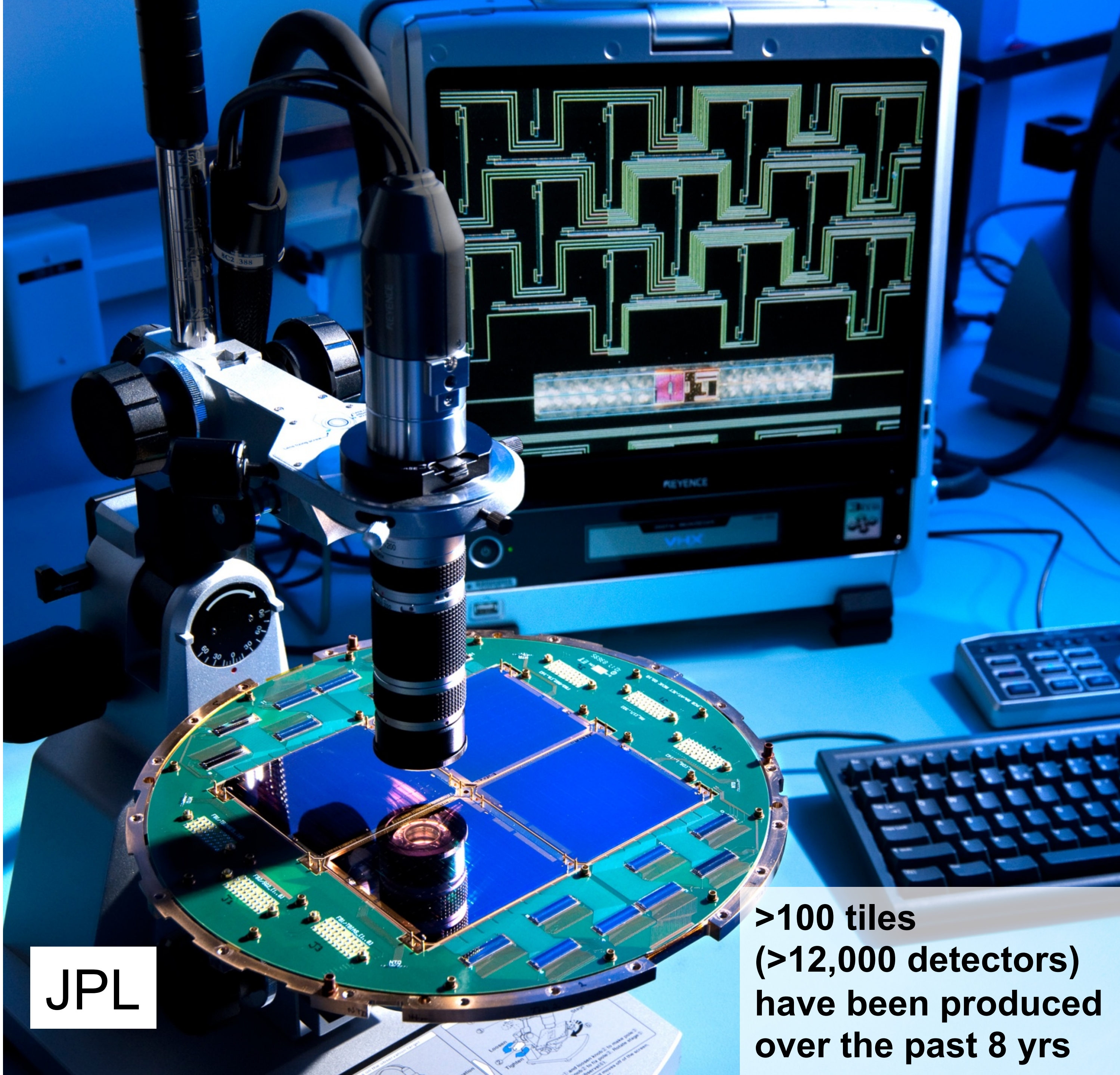
Mass-produced superconducting detectors from JPL

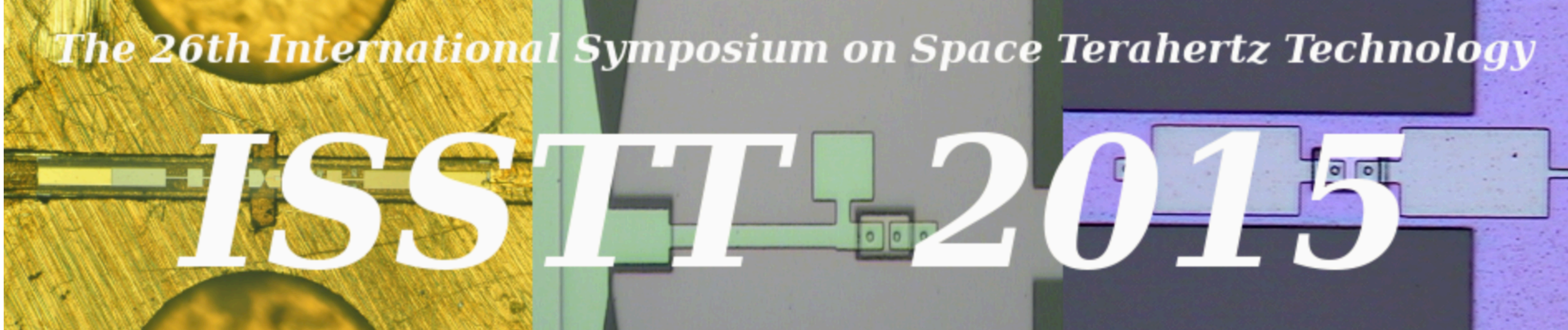


Detecting the CMB radiation

BICEP2 Detector: Transition-Edge Superconductor




JPL
>100 tiles
(>12,000 detectors)
have been produced
over the past 8 yrs



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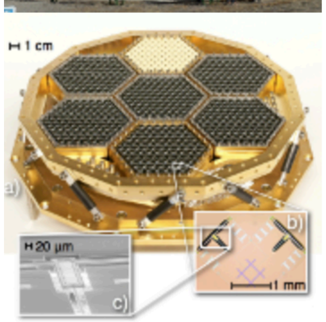
- Abstracts
- SOC & LOC
- Registration
- Accommodations



March 16 - 18, 2015

google "ISSTT"

Cambridge, Massachusetts, U.S.A.

The **Harvard-Smithsonian Center for Astrophysics** will be hosting the 26th International Symposium on Space Terahertz Technology, which will take place from March 16th through March 18th 2015 at the Knafel Center in the Radcliffe Yard on the Harvard University campus in Cambridge Massachusetts.

Scope

The meeting will focus on millimeter, submillimeter, and Terahertz technology and applications, including:

Ultra-sensitive detectors

Sources and instrumentation

Optical design and measurement techniques

Back end signal processors

Applications of receivers and detector systems

CMB technology will be a focus!

REGISTRATION NOW OPEN!!!

Scientific Organizing Committee Members

- Andrey Baryshev (Space Research Organization of Netherlands, The Netherlands)
- Victor Belitsky (Chalmers University, Sweden)
- Raymond Blundell (Smithsonian Astrophysical Observatory, USA)
- Gregory Gol'tsman (Moscow State Pedagogical University, Russia)

South Pole CMB telescopes

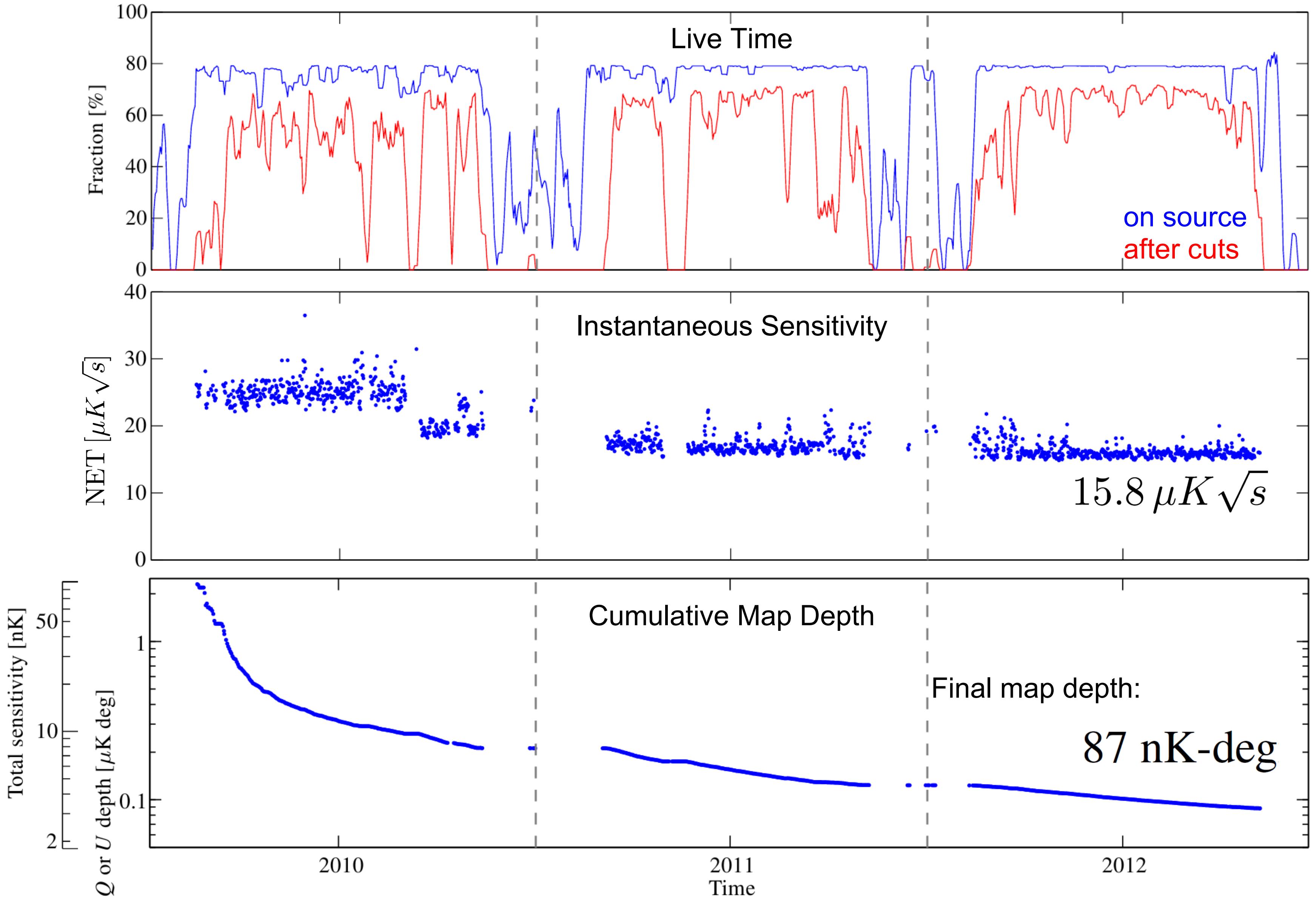
NSF's South Pole Station:
A popular place with CMB Experimentalists!

Dry, stable atmosphere and 24h coverage of "Southern Hole".

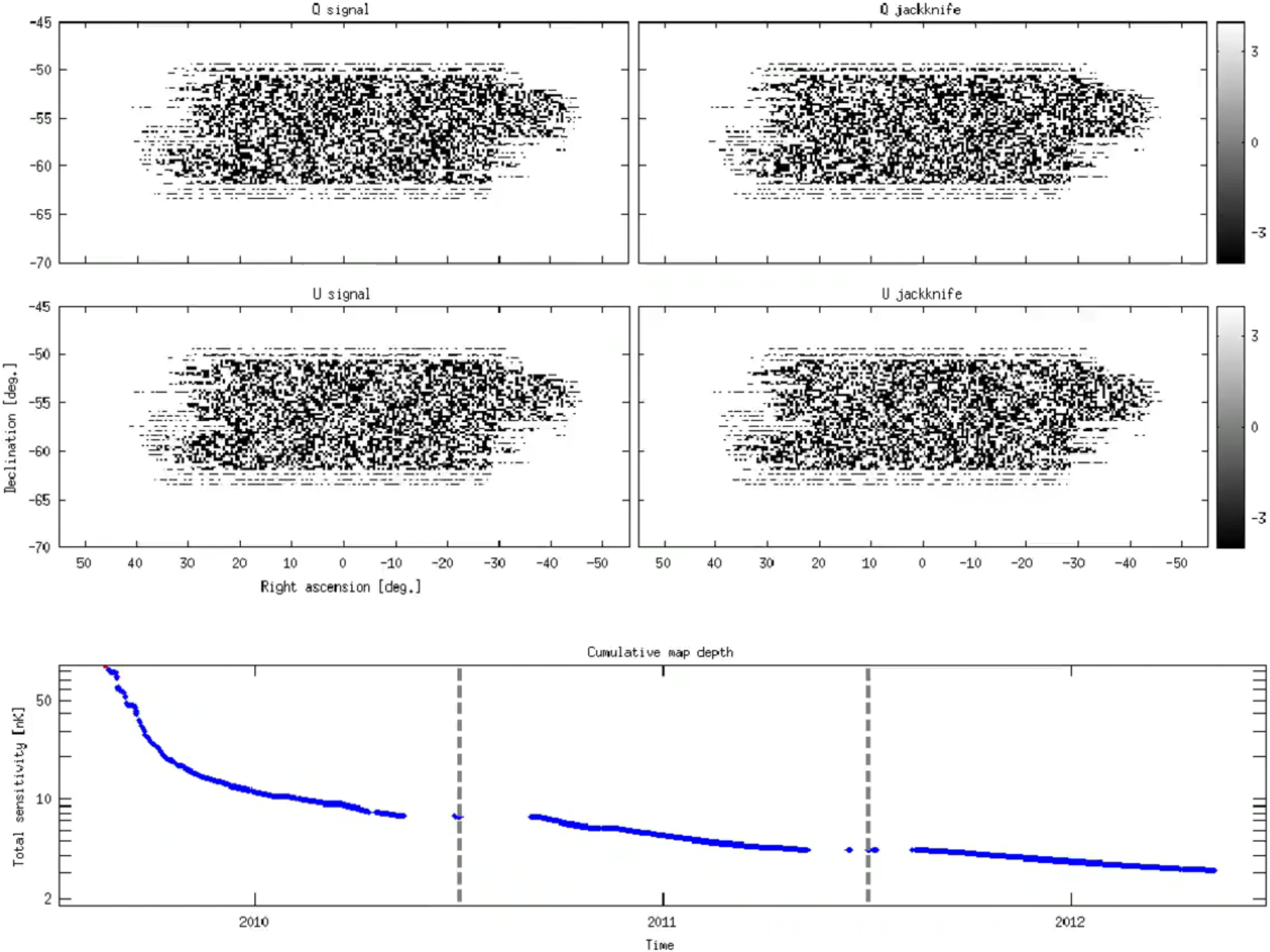
Atacama offers a proven & developed excellent alternative site.
Greenland, Tibet may offer viable sites for northern coverage

South Pole: “Relentless Observing”

BICEP2 3-year Data Set

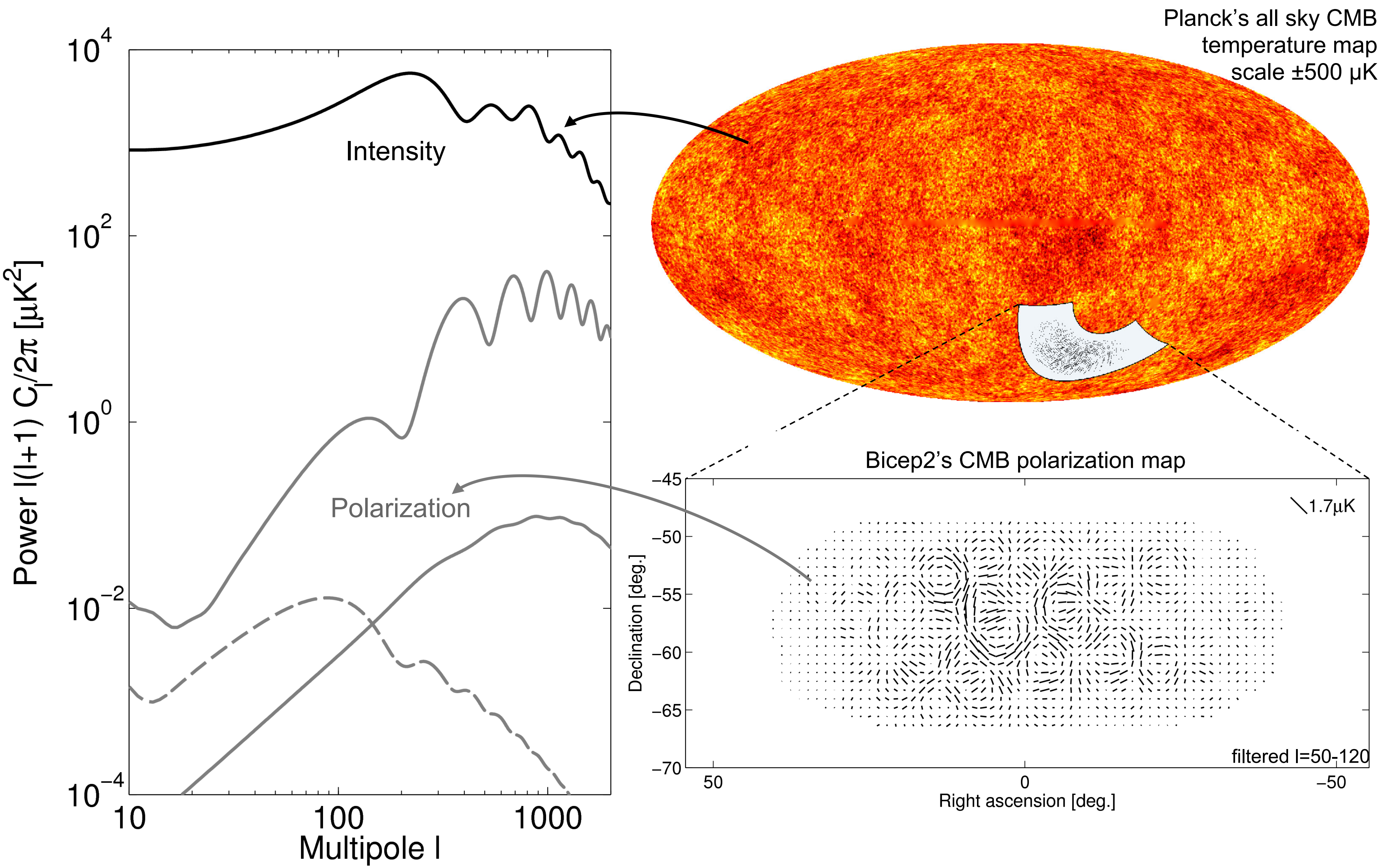


John Kovac for The Bicep2 Collaboration



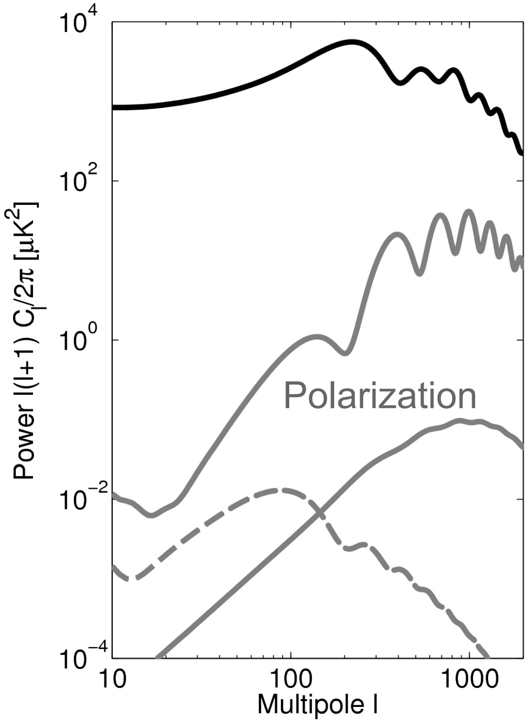
Q signal
Q jackknife
U signal
U jackknife
Declination [deg.]
Right ascension [deg.]
mK
Cumulative map depth
Total sensitivity [nK]
Time
2010
2011
2012

Cosmic Microwave Background

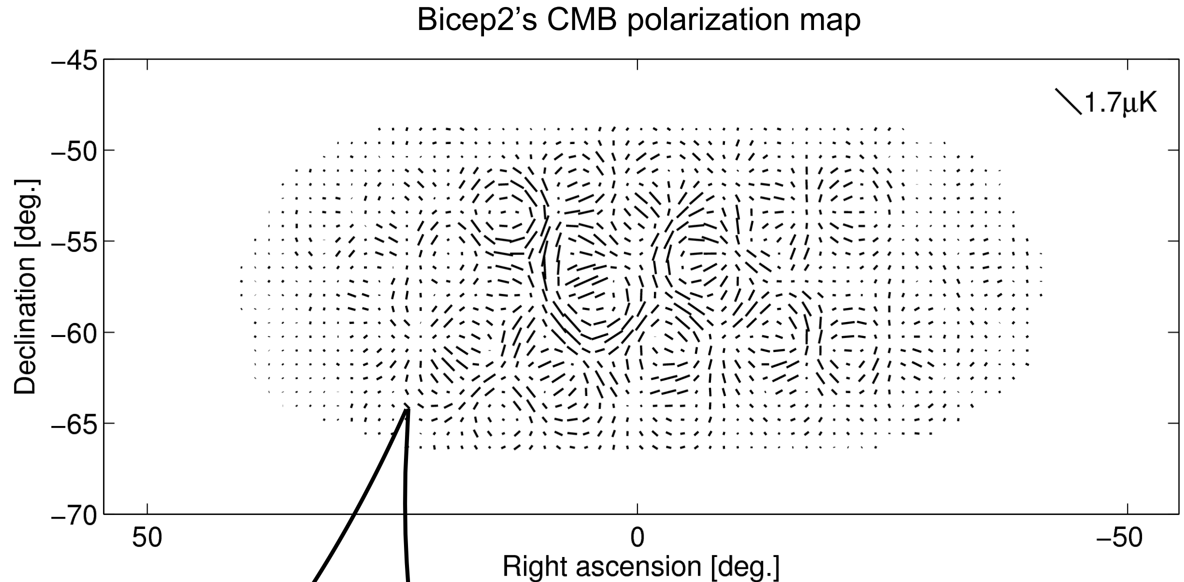


The Bicep2 Collaboration

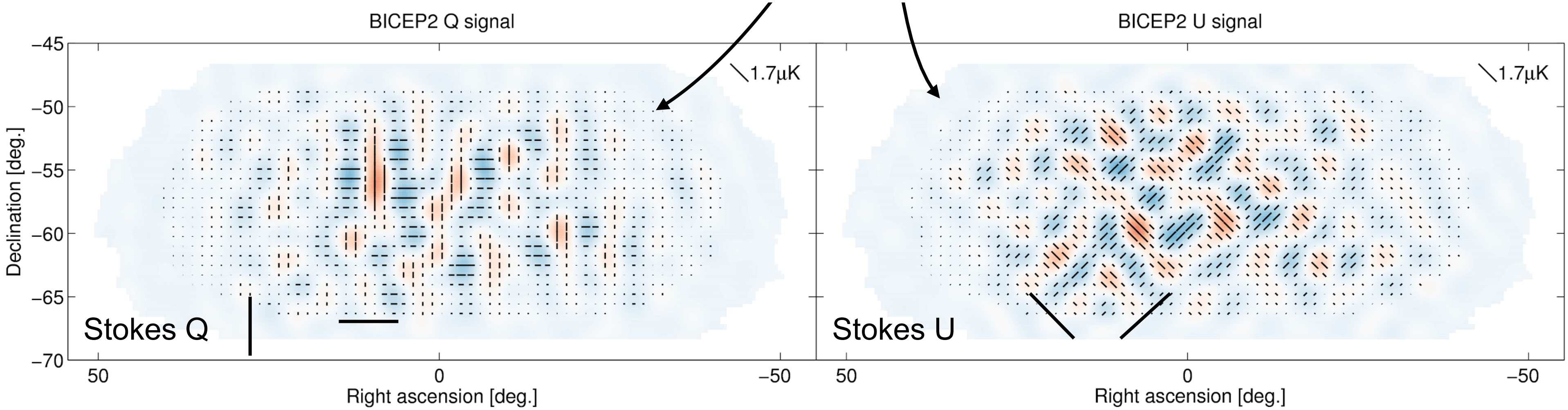
CMB Polarization



Need 2D basis to describe polarization map...

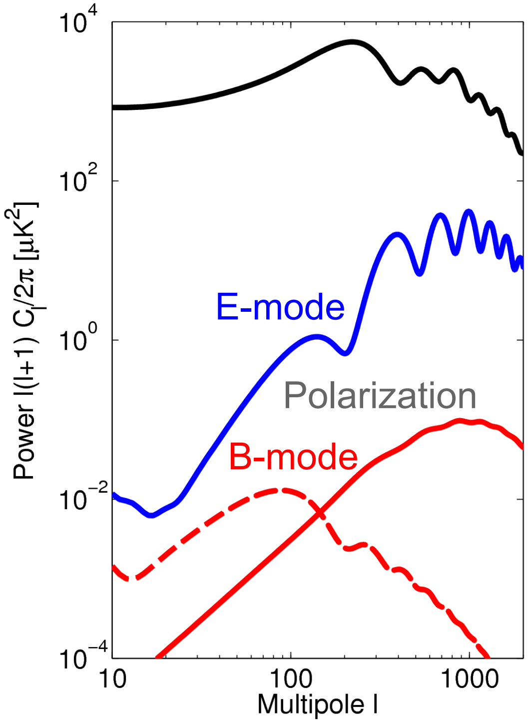


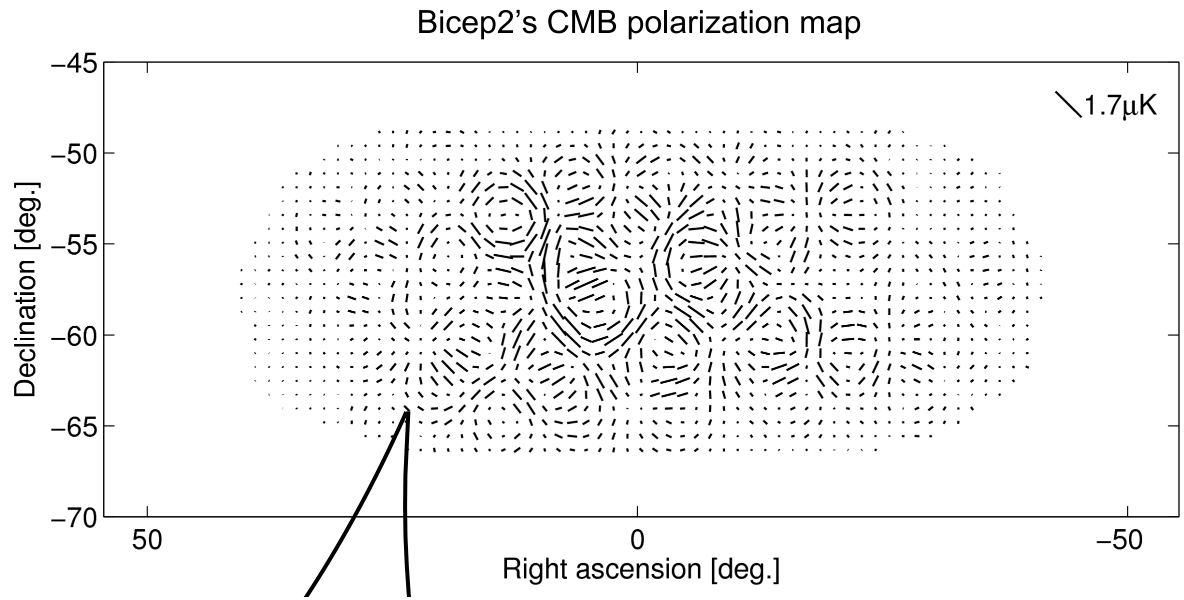
...familiar choice: Stokes Parameters Q&U



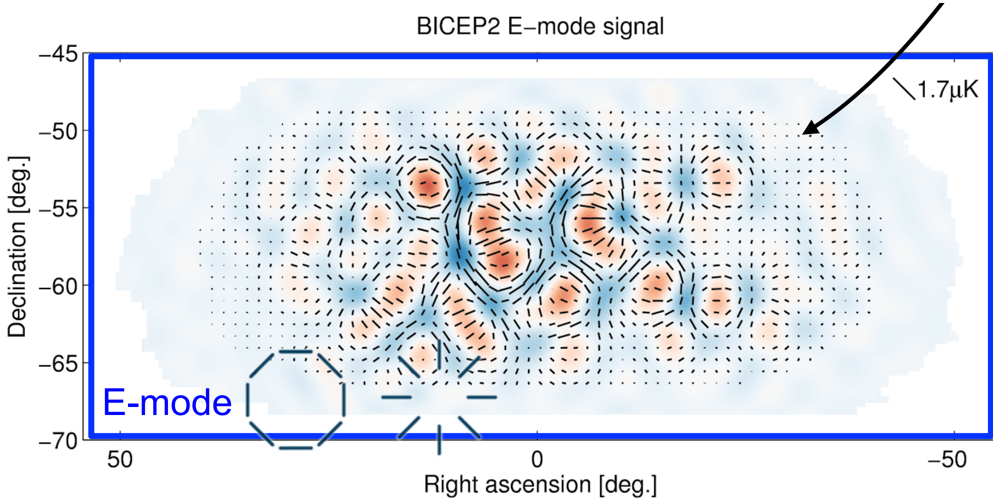
The Bicep2 Collaboration

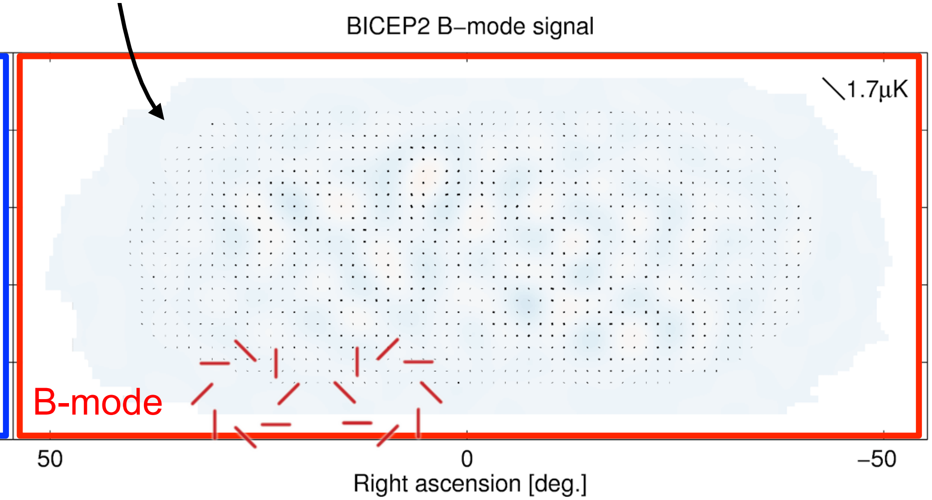
CMB Polarization





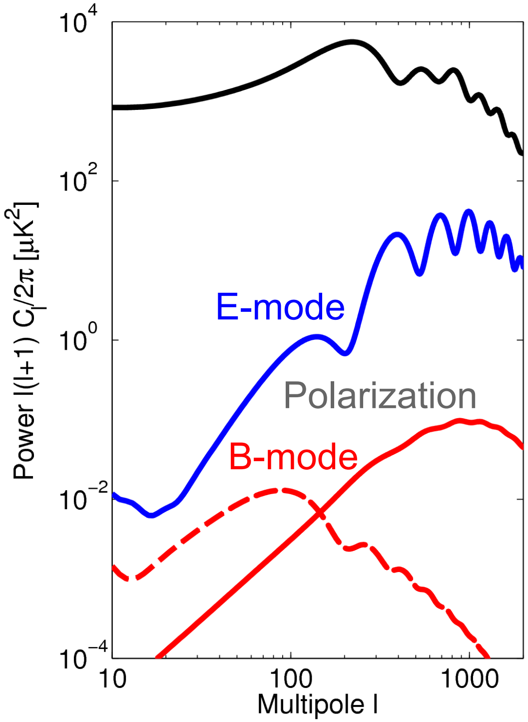
…map eigenmode-based B separation for highest fidelity

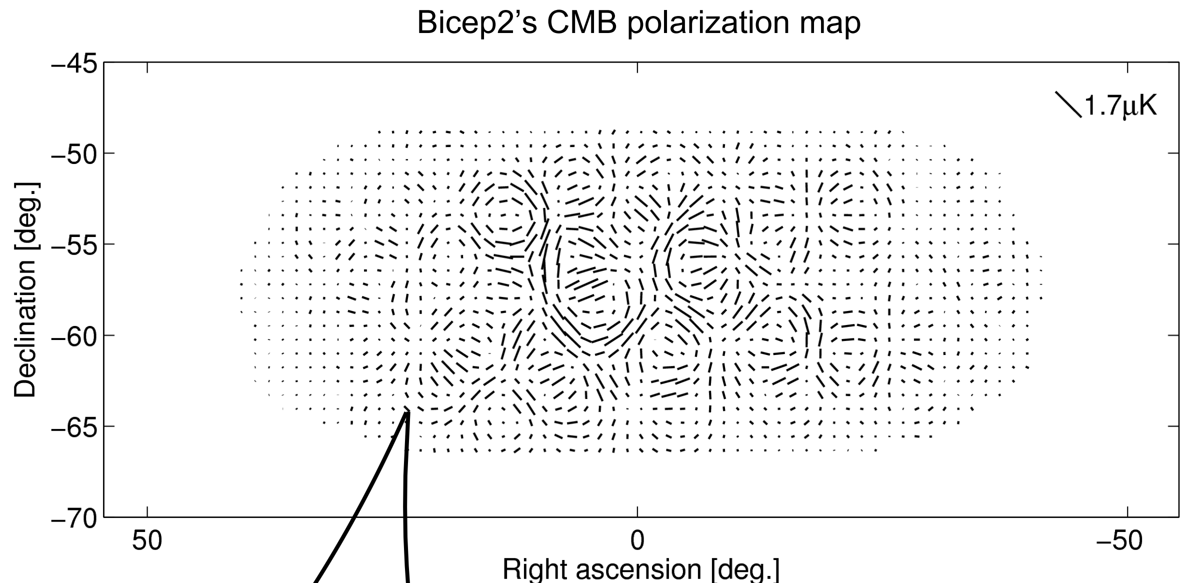




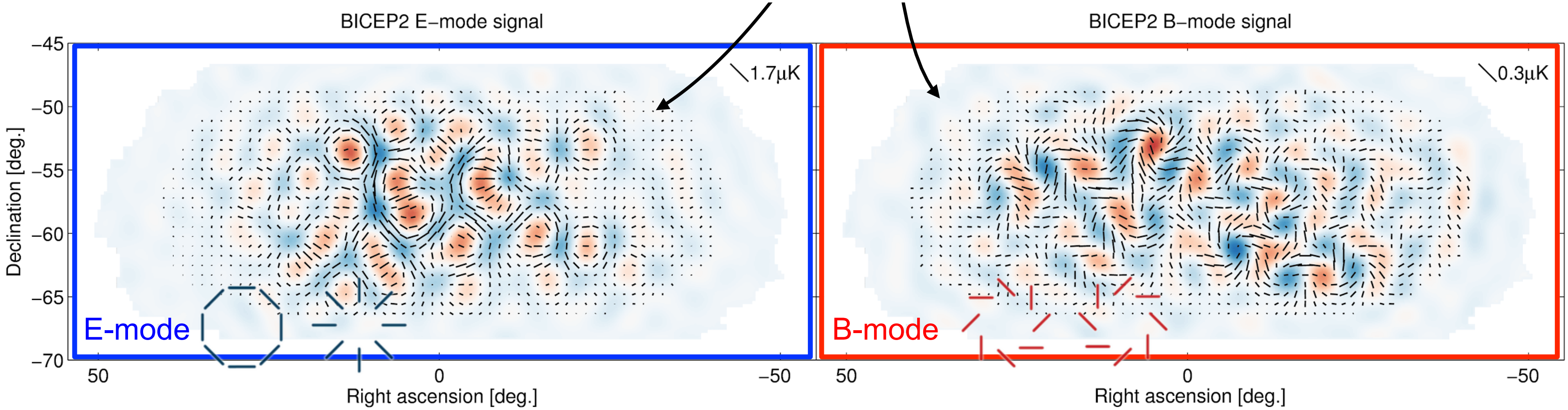
The Bicep2 Collaboration

CMB Polarization



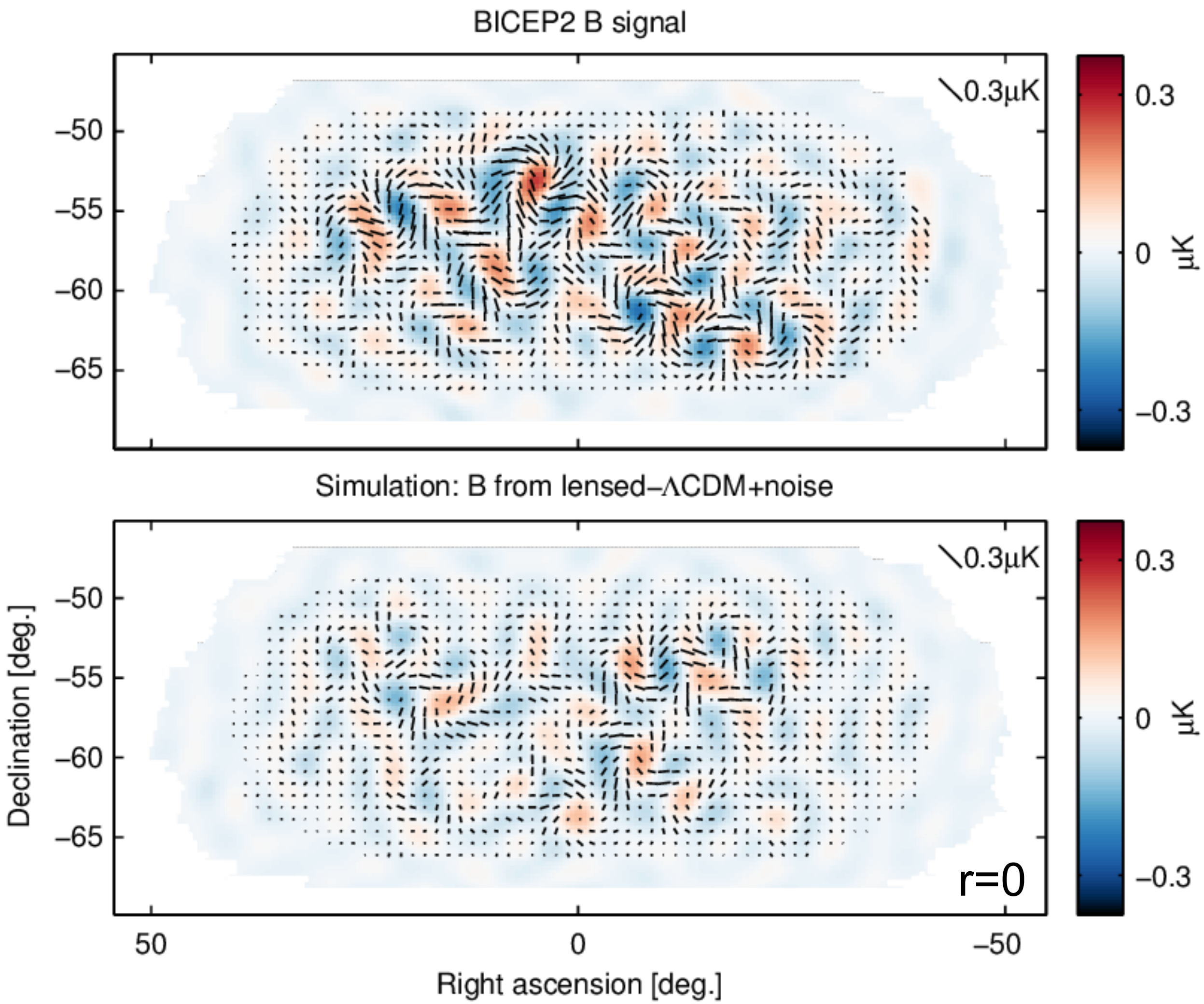


…map eigenmode-based B separation for highest fidelity



The Bicep2 Collaboration

B-mode Map vs. Simulation



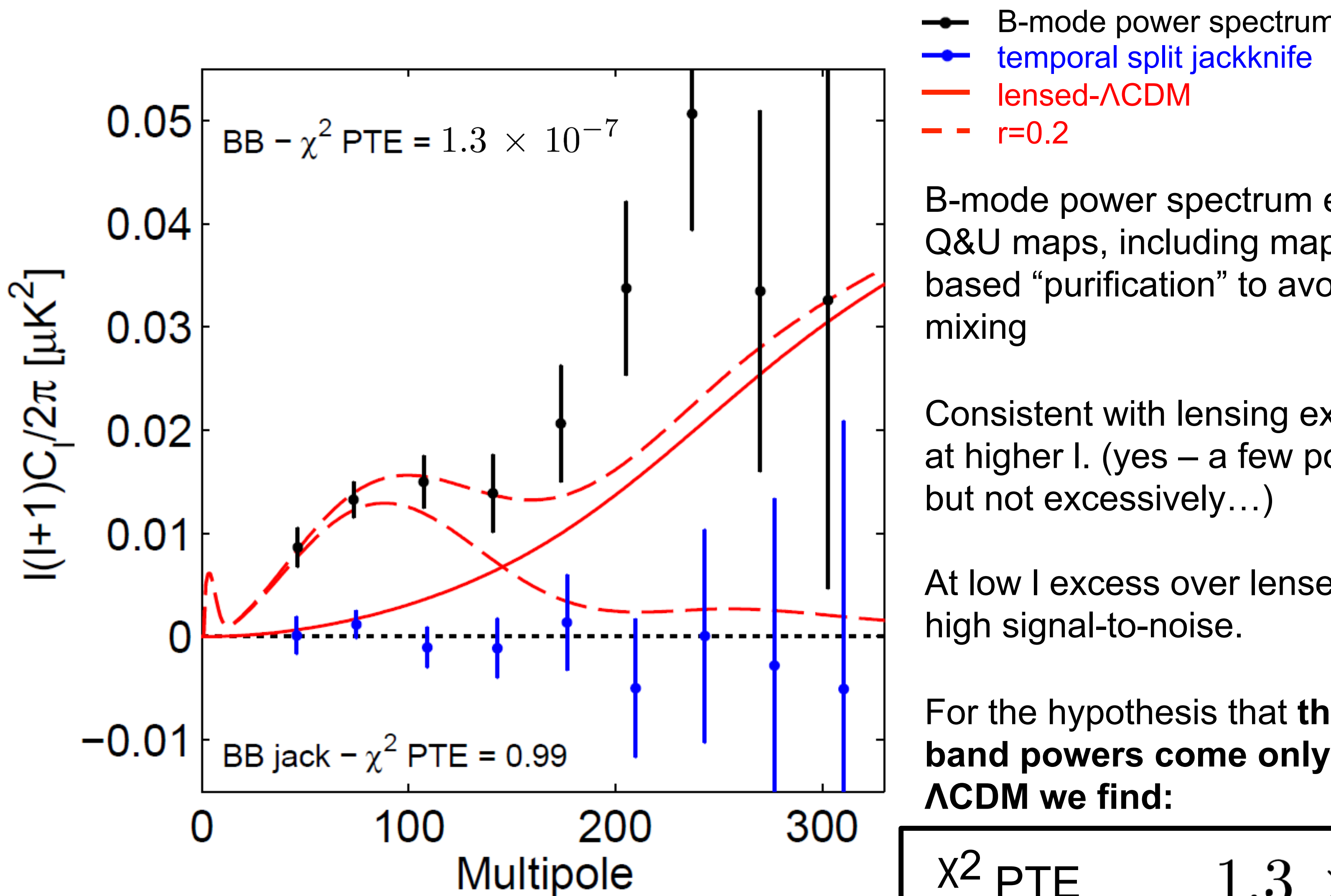
Analysis “calibrated” using lensed-ΛCDM+noise simulations.

The simulations repeat the full observation at the timestream level - including all filtering operations.

We perform various filtering operations: Use the sims to correct for these

Also use the sims to derive the final uncertainties (error bars)

BICEP2 B-mode Power Spectrum



B-mode power spectrum estimated from Q&U maps, including map based "purification" to avoid E→B mixing

Consistent with lensing expectation at higher l. (yes – a few points are high but not excessively…)

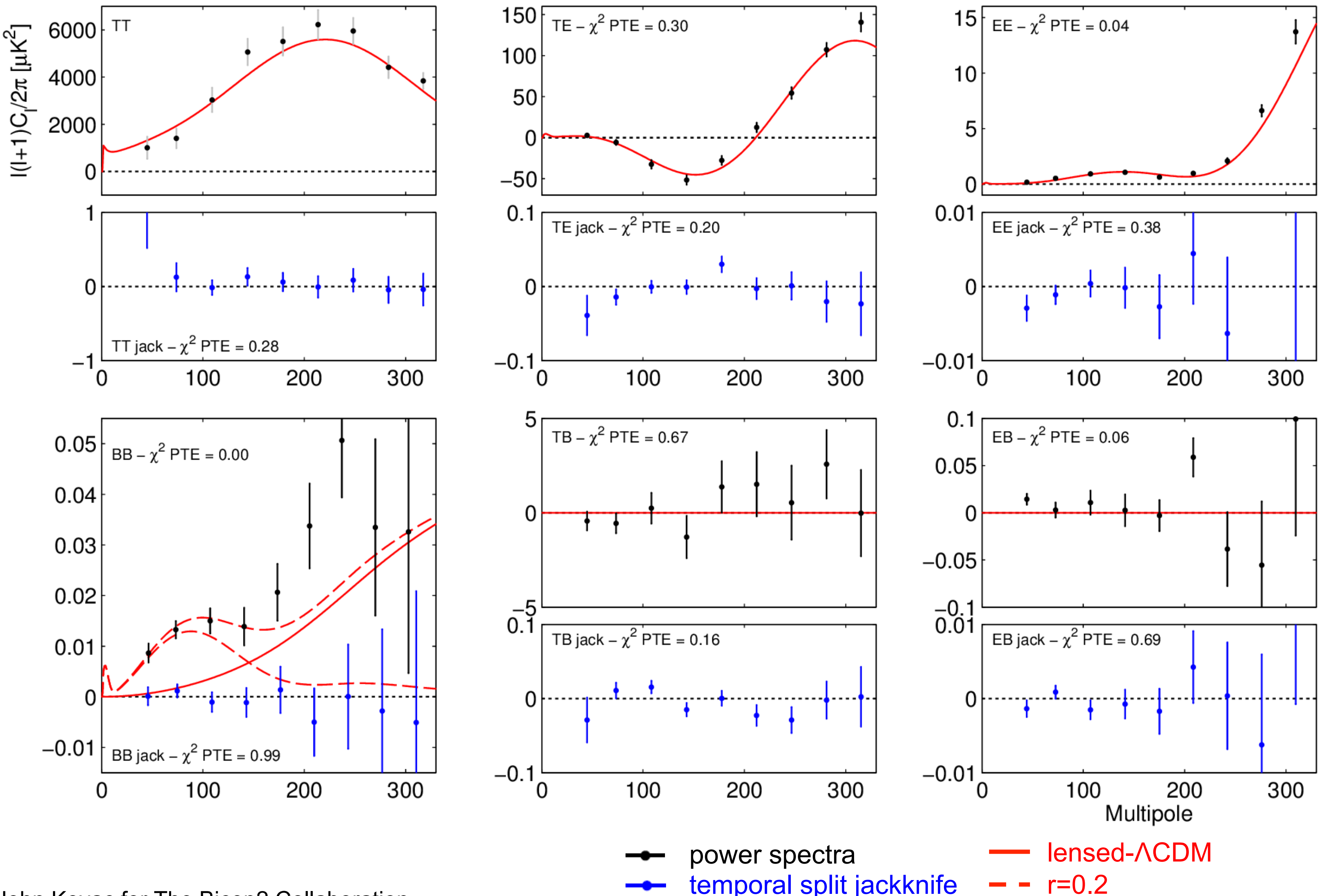
At low l excess over lensed-ΛCDM with high signal-to-noise.

For the hypothesis that **the measured band powers come only from lensed-ΛCDM we find:**

χ^2 PTE	1.3×10^{-7}
significance	$5.3\,\sigma$

John Kovac for The Bicep2 Collaboration

Temperature and Polarization Spectra



John Kovac for The Bicep2 Collaboration

Check Systematics: Jackknifes

TABLE 1
JACKKNIFE PTE VALUES FROM χ^2 AND χ (SUM-OF-DEVIATION) TESTS

Jackknife	Bandpowers 1–5 χ^2	Bandpowers 1–9 χ^2	Bandpowers 1–5 χ	Bandpowers 1–9 χ
Deck jackknife				
EE	0.046	0.030	0.164	0.299
BB	0.774	0.329	0.240	0.082
EB	0.337	0.643	0.204	0.267
Scan Dir jackknife				
EE	0.483	0.762	0.978	0.938
BB	0.531	0.573	0.896	0.551
EB	0.898	0.806	0.725	0.890
Tag Split jackknife				
EE	0.541	0.377	0.916	0.938
BB	0.902	0.992	0.449	0.585
EB	0.477	0.689	0.856	0.615
Tile jackknife				
EE	0.004	0.010	0.000	0.002
BB	0.794	0.752	0.565	0.331
EB	0.172	0.419	0.962	0.790
Phase jackknife				
EE	0.673	0.409	0.126	0.339
BB	0.591	0.739	0.842	0.944
EB	0.529	0.577	0.840	0.659
Mux Col jackknife				
EE	0.812	0.587	0.196	0.204
BB	0.826	0.972	0.293	0.283
EB	0.866	0.968	0.876	0.697
Alt Deck jackknife				
EE	0.004	0.004	0.070	0.236
BB	0.397	0.176	0.381	0.086
EB	0.150	0.060	0.170	0.291
Mux Row jackknife				
EE	0.052	0.178	0.653	0.739
BB	0.345	0.361	0.032	0.008
EB	0.529	0.226	0.024	0.048
Tile/Deck jackknife				
EE	0.048	0.088	0.144	0.132
BB	0.908	0.840	0.629	0.269
EB	0.050	0.154	0.591	0.591
Focal Plane inner/outer jackknife				
EE	0.230	0.597	0.022	0.090
BB	0.216	0.531	0.046	0.092
EB	0.036	0.042	0.850	0.838
Tile top/bottom jackknife				
EE	0.289	0.347	0.459	0.599
BB	0.293	0.236	0.154	0.028
EB	0.545	0.683	0.902	0.932
Tile inner/outer jackknife				
EE	0.727	0.533	0.128	0.485
BB	0.255	0.086	0.421	0.036
EB	0.465	0.737	0.208	0.168
Moon jackknife				
EE	0.499	0.689	0.481	0.679
BB	0.144	0.287	0.898	0.858
EB	0.289	0.359	0.531	0.307
A/B offset best/worst				
EE	0.317	0.311	0.868	0.709
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

14 jackknife tests applied to 3 spectra, 4 statistics

Splits the 4 boresight rotations

Amplifies differential pointing in comparison to fully added data. Important check of deprojection. See later slides.

Splits by time

Checks for contamination on long ("Temporal Split") and short ("Scan Dir") timescales. Short timescales probe detector transfer functions.

Splits by channel selection

Checks for contamination in channel subgroups, divided by focal plane location, tile location, and readout electronics grouping

Splits by possible external contamination

Checks for contamination from ground-fixed signals, such as polarized sky or magnetic fields, or the moon

Splits to check intrinsic detector properties

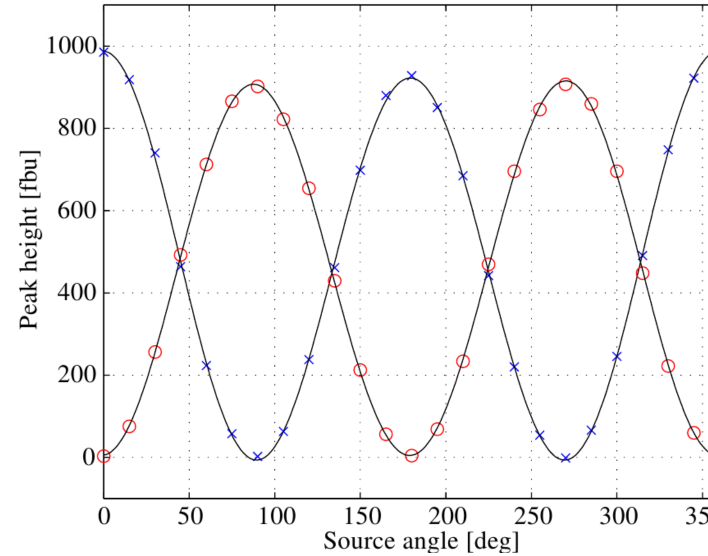
Checks for contamination from detectors with best/worst differential pointing. "Tile/dk" divides the data by the orientation of the detector on the sky.

Calibration Measurements

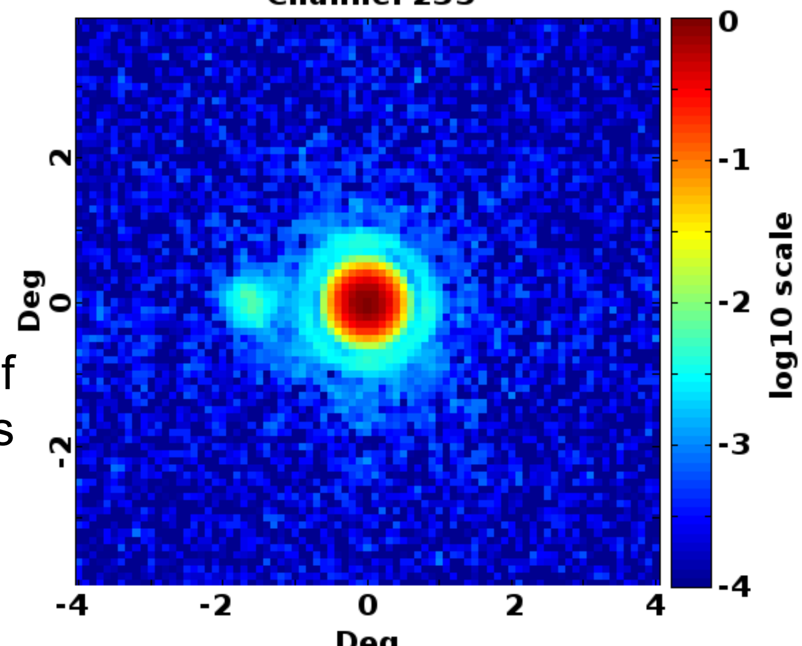
For instance...

Far field beam mapping

Detector Polarization Calibration



Channel 235



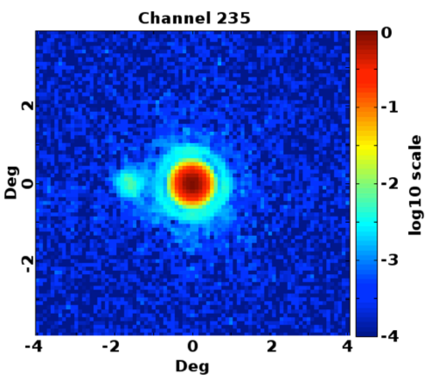
Hi-Fi beam maps of individual detectors

Detailed description in companion Instrument Paper

We know our Beam Shapes

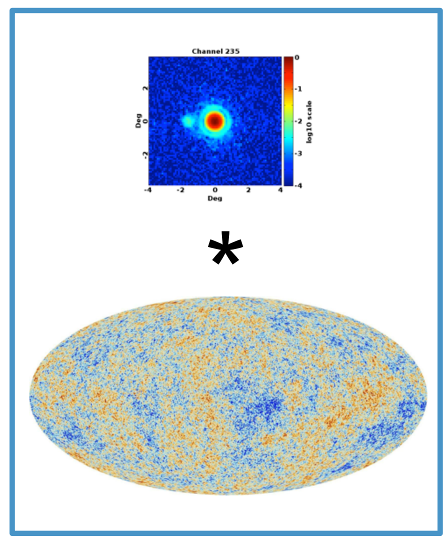
Because contamination from beam shape mismatch is entirely deterministic, we can both **filter it out (deprojection)** **and** **predict it in simulation** using calibration data and Planck T map as input.

Calibration data for each channel

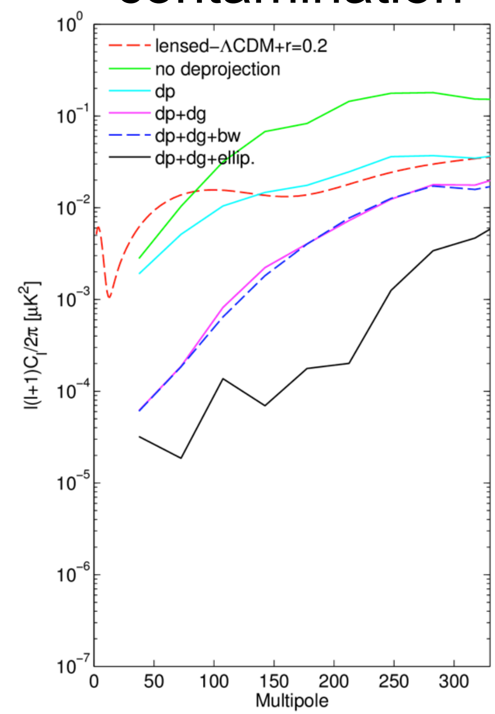


Simulation

(explicit convolution with Planck T map)

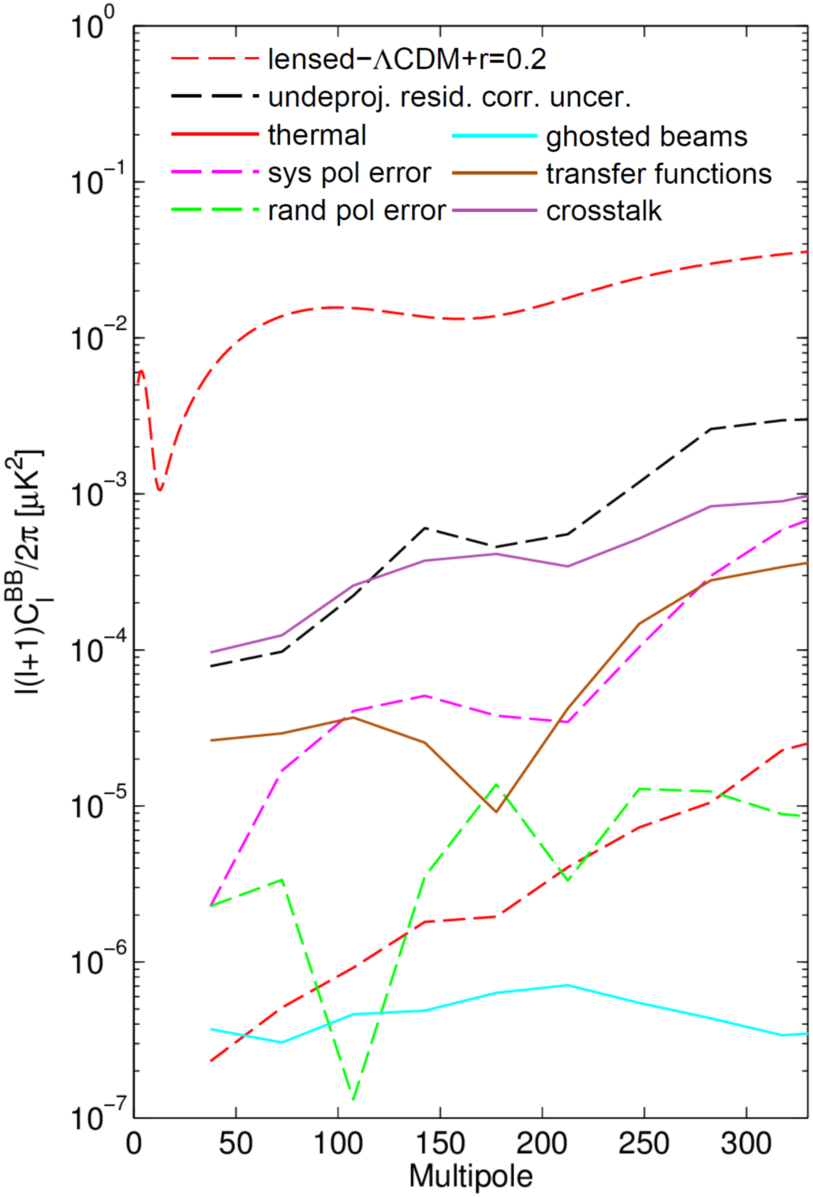


Predictions of contamination



analysis by Chris Sheehy, Chin Lin Wong

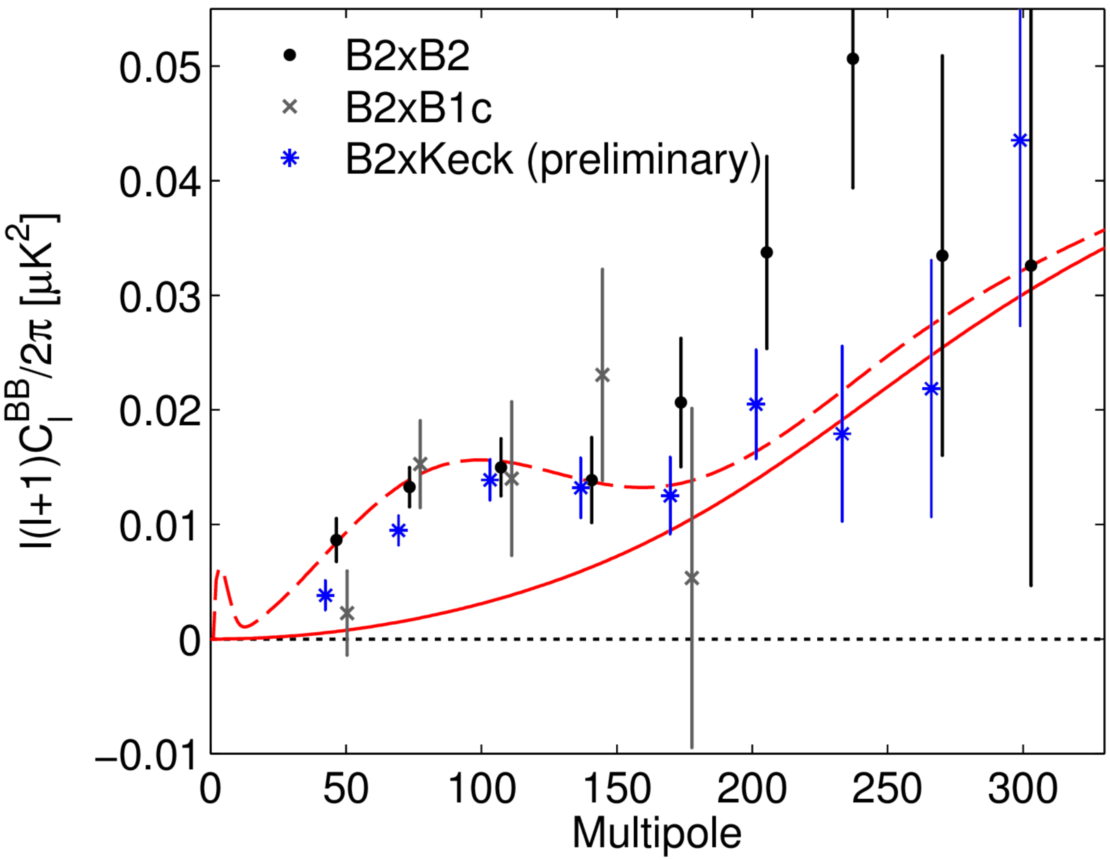
Systematics beyond Beam imperfections



All systematic effects that we could imagine were investigated.

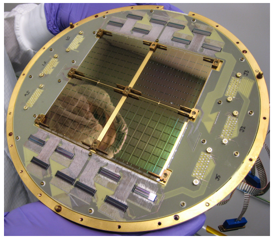
We find with high confidence that the apparent signal *cannot be explained* by instrumental systematics!

March 2014: Cross Spectra between 3 Experiments



~3σ evidence of excess power in the B2 x BICEP1 (100+150 GHz) cross spectrum

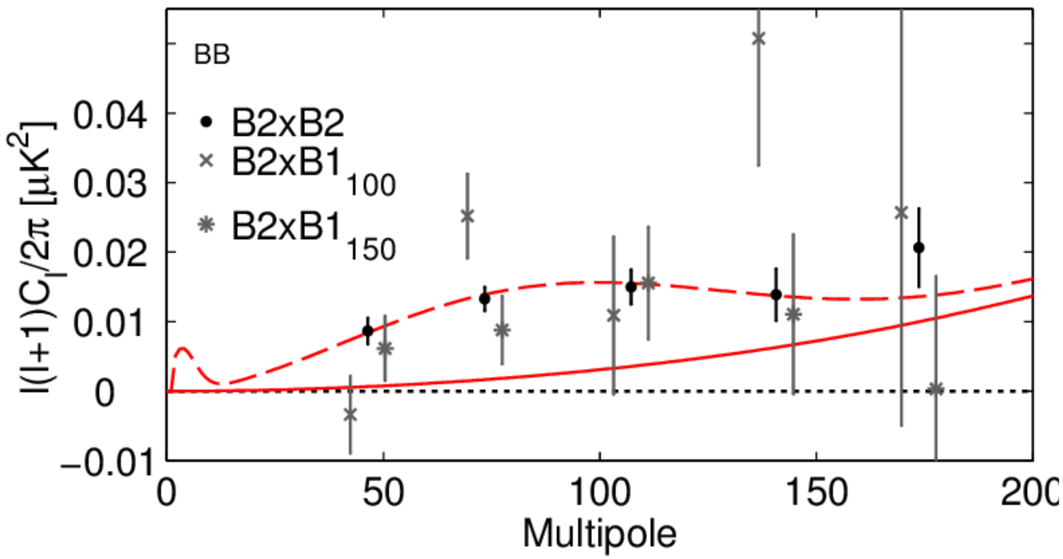
Excess power is also evident in the B2 x Keck 2012/13 (150 GHz) cross spectrum



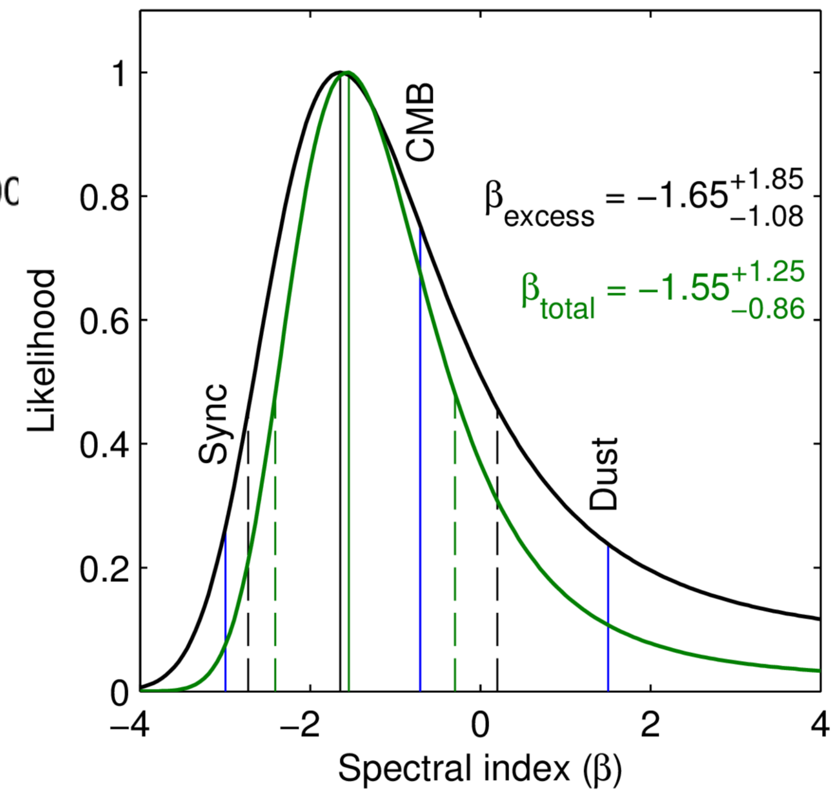
Cross spectra:
Powerful additional evidence against a systematic origin of the apparent signal

John Kovac for The Bicep2 Collaboration

March 2014: Spectral Index of the B-mode Excess

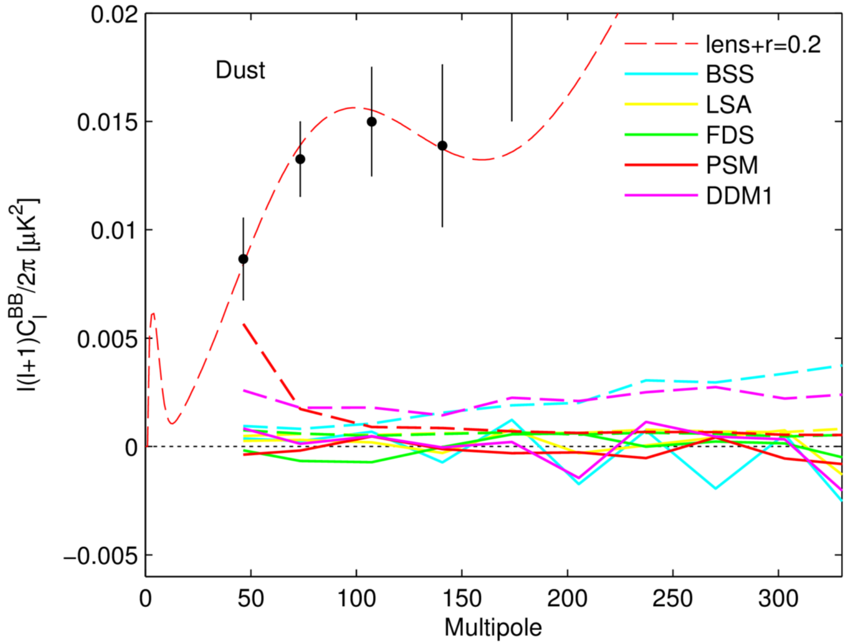


Likelihood ratio test: consistent with CMB spectrum, disfavor pure dust for excess at **1.7σ**



Comparison of B2 auto with B2$_{\mathbf{150}}$ x B1$_{\mathbf{100}}$ constrains signal frequency dependence, independent of foreground projections, but only with very modest significance.

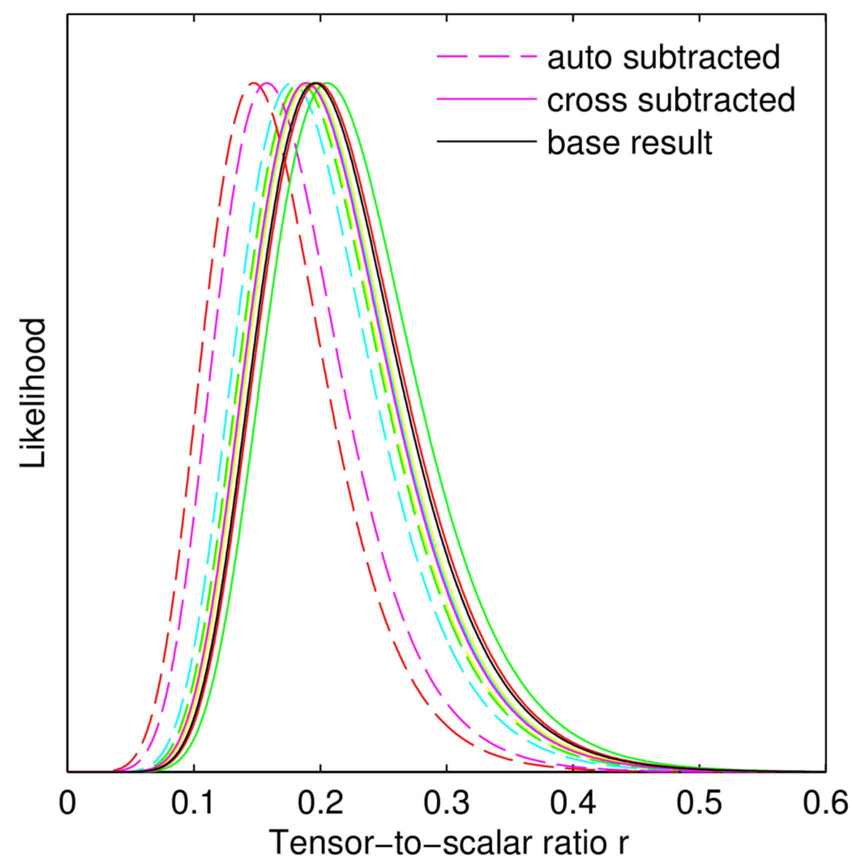
March 2014: Constraint on r under Foreground Projections



"Probability that each of these models reflect reality is hard to assess" – uncertainties could go in either direction, but large enough to equal entire signal.

r = 0.15 to 0.19, *based on these models* at default values.

Adjust likelihood curve by subtracting the dust projection auto and cross spectra from our bandpowers:



BICEP2 I: Detection of B-mode Polarization at Degree Angular Scales

BICEP2 Collaboration - P. A. R. Ade,[1] R. W. Aikin,[2] D. Barkats,[3] S. J. Benton,[4] C. A. Bischoff,[5] J. J. Bock,[2,6] J. A. Brevik,[2] I. Buder,[5] E. Bullock,[7] C. D. Dowell,[6] L. Duband,[8] J. P. Filippini,[2] S. Fliescher,[9] S. R. Golwala,[2] M. Halpern,[10] M. Hasselfield,[10] S. R. Hildebrandt,[2,6] G. C. Hilton,[11] V. V. Hristov,[2] K. D. Irwin,[12,13,11] K. S. Karkare,[5] J. P. Kaufman,[14] B. G. Keating,[14] S. A. Kernasovskiy,[12] J. M. Kovac,[5,*] C. L. Kuo,[12,13] E. M. Leitch,[15] M. Lueker,[2] P. Mason,[2] C. B. Netterfield,[4,16] H. T. Nguyen,[6] R. O'Brient,[6] R. W. Ogburn IV,[12,13] A. Orlando,[14] C. Pryke,[9,7,†] C. D. Reintsema,[11] S. Richter,[5] R. Schwarz,[9] C. D. Sheehy,[9,15] Z. K. Staniszewski,[2,6] R. V. Sudiwala,[1] G. P. Teply,[2] J. E. Tolan,[12] A. D. Turner,[6] A. G. Vieregg,[5,15] C. L. Wong,[5] and K. W. Yoon[12,13]

We report results from the BICEP2 experiment, a Cosmic Microwave Background (CMB) polarimeter specifically designed to search for the signal of inflationary gravitational waves in the B-mode power spectrum around $\ell \sim 80$. The telescope comprised a 26 cm aperture all-cold refracting optical system equipped with a focal plane of 512 antenna coupled transition edge sensor (TES) 150 GHz bolometers each with temperature sensitivity of $\approx 300 \ \ \mu K_{\text{CMB}}\sqrt{s}$. BICEP2 observed from the South Pole for three seasons from 2010 to 2012. A low-foreground region of sky with an effective area of 380 square degrees was observed to a depth of 87 nK-degrees in Stokes Q and U. In this paper we describe the observations, data reduction, maps, simulations and results. We find an excess of B-mode power over the base lensed-ΛCDM expectation in the range $30 < \ell < 150$, inconsistent with the null hypothesis at a significance of $> 5\sigma$. Through jackknife tests and simulations based on detailed calibration measurements we show that systematic contamination is much smaller than the observed excess. Cross correlating against WMAP 23 GHz maps we find that Galactic synchrotron makes a negligible contribution to the observed signal. We also examine a number of available models of polarized dust emission and find that at their default parameter values they predict power $\sim 5 - 10\times$ smaller than the observed excess signal (with no significant cross-correlation with our maps). However, these models are not sufficiently constrained by external public data to exclude the possibility of dust emission bright enough to explain the entire excess signal. Cross-correlating BICEP2 against 100 GHz maps from the BICEP1 experiment, the excess signal is confirmed with 3σ significance and its spectral index is found to be consistent with that of the CMB, disfavoring dust at 1.7σ. The observed B-mode power spectrum is well-fit by a lensed-ΛCDM + tensor theoretical model with tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with $r = 0$ disfavored at 7.0σ. Accounting for the contribution of foreground dust will shift this value downward by an amount which will be better constrained with upcoming datasets.

arXiv:1403.3985 / published PRL June 19

Timeline Since March 2014…

- Many early instrumental / stat queries… mostly seem to have faded
- Major outstanding issue:

  Polarized dust foreground may be stronger than previously projected…

  March 18: J. L. Puget: "For certainty, dust maps must be subtracted; wait for Planck"
- May: 4 new papers on dust polarization appeared from Planck
  - –mid-latitude only; faintest regions excluded where systematics and noise dominated.
  - –Trend to higher polarization in low dust regions. 4% avg (i.e. consistent w/ models), but > 10% in some regions – spatial variation of polarized power not yet understood!
- June: PRL final version of paper published:

  Uncertainty on interpretation has increased: **"Is it all dust?"**

  BICEP2(+1) internal constraints are weak. Dust models appear not to be reliable.

  B-mode detection + analysis are secure – the measurements work!

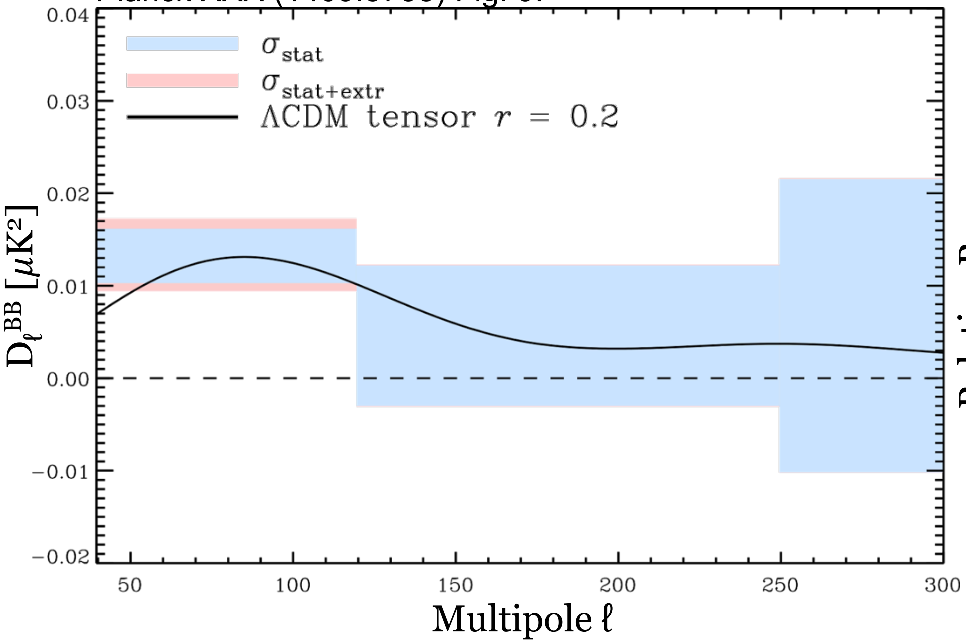
  Getting new data remains more important than ever.

- July: Joint Analysis begun with Planck, combining maps to cross spectra

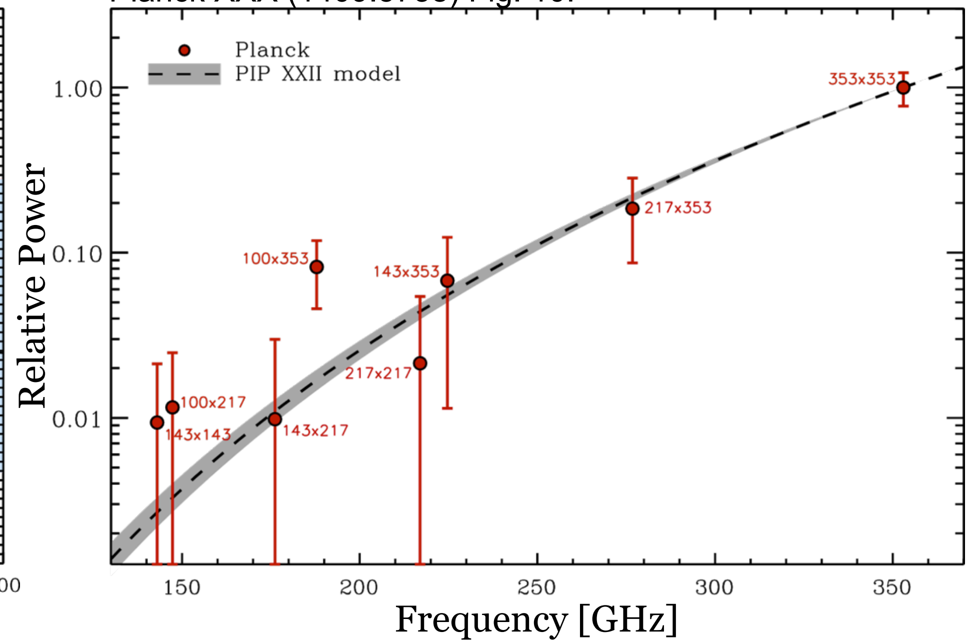
- September: PIP-XXX released, including high-latitude dust study

September 2014: Planck XXX

Planck XXX (1409.5738) Fig. 9:



Planck XXX (1409.5738) Fig. 10:



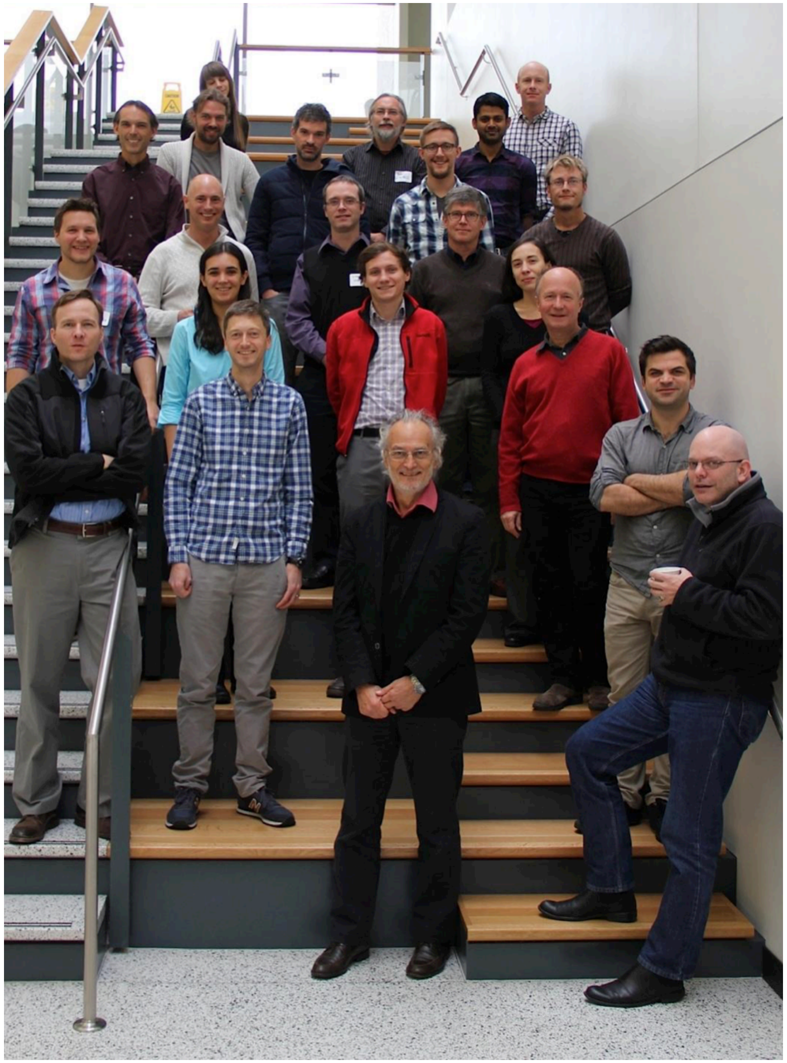
- ➢ In a single broad bin roughly matches the power seen by BICEP2
- ➢ **Planck XXX paper states:**
  “ The present uncertainties are large and will be reduced through an ongoing, joint analysis of the Planck and BICEP2 data sets. ”

- ➢ The 353x353 spectrum scaled to 150 GHz (Bicep2’s frequency)
- ➢ SED and uncertainty is derived from average over large sky fraction – Planck XXX finds no evidence of departures of polarized dust from this scaling.

  “Good news for component separation” – F. Boulanger

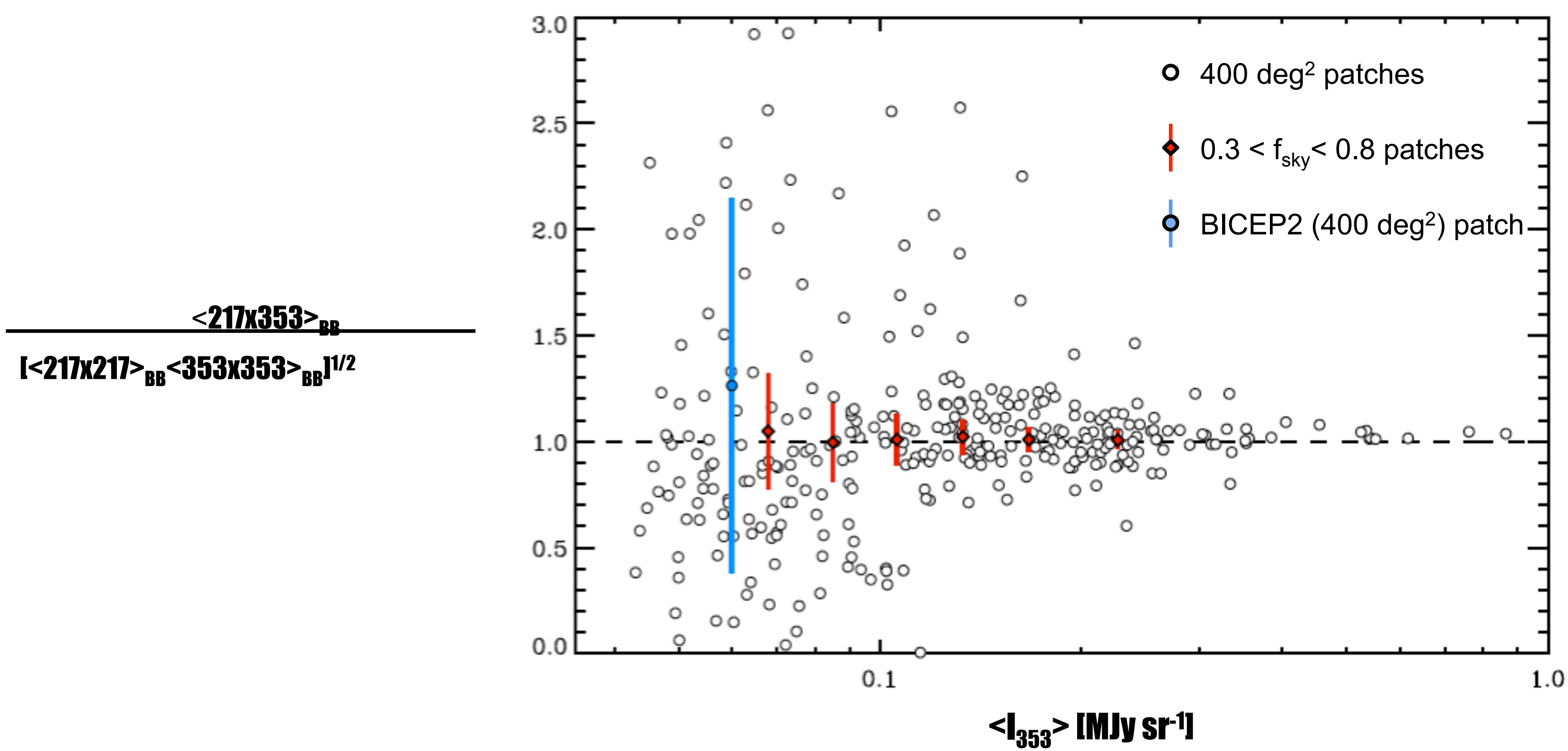
Coming next (1): BICEP2 + Planck Joint analysis

- SOON. Unfortunately can't discuss results today!
- The combination of B2 and Planck is far more powerful than either alone
- Collaborative effort has been extremely fruitful (+ enjoyable)
- Exchange of maps, full filtering matrices, signal and noise simulations, cross-checks of power spectrum estimators – good template for future joint analyses
- Analysis invokes all spectra and cross spectra
- Multi-component, parametric CMB+foreground analysis for likelihood
  - full data release, spectra and likelihood code
- Timeline has allowed inclusion of full Keck 2012+13 150 GHz datasets



Limits on astrophysical decorrelation

- Consistency of dust amplitude in Planck 353 and 217 GHz BB auto spectra with dust amplitude in the cross spectrum limits possible spatial decorrelation of dust signal between frequencies (e.g. from a spatially varying color spectral index).
- Averaging over the 400 deg^2 patches yields a mean decorrelation ratio **d = 1.01 ± 0.07.**
- Averaging over the six $0.3 < f_{sky} < 0.8$ patches yields **d = 1.01 ± 0.03.**

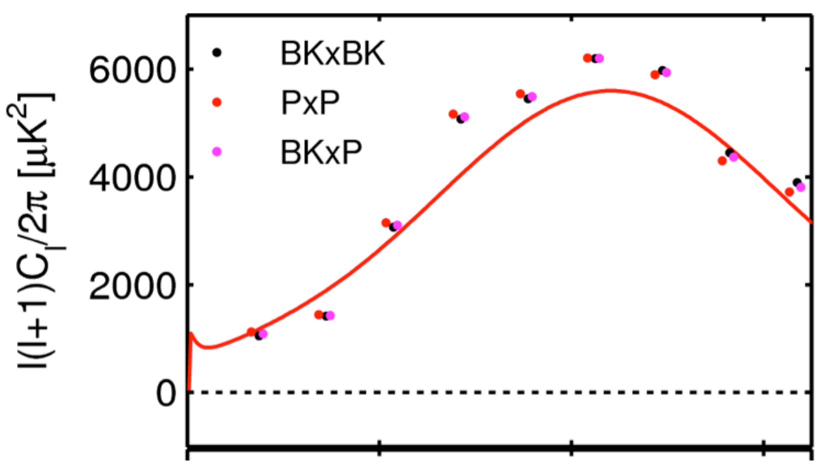


Bicep2, Keck Array and Planck Collaboration

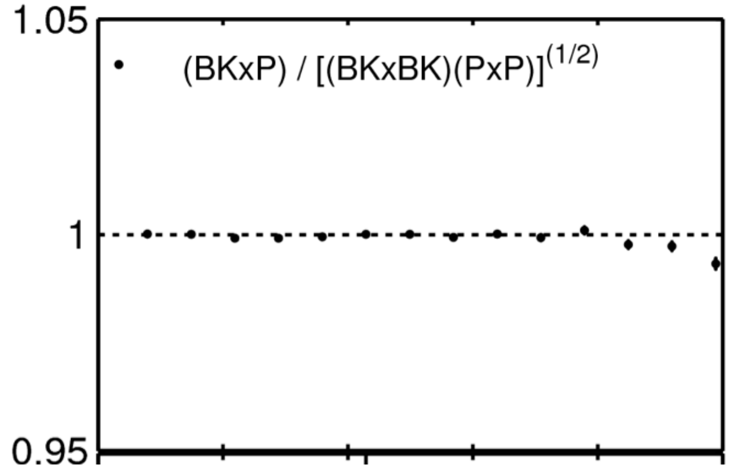
Limits on systematic decorrelation

- Consistency of B2K and Planck 143 GHz year-split TT auto spectra with the cross spectrum limits possible decorrelation from pointing error, pipeline errors, etc. Weighted mean over multipole yields decorrelation ratio d = 0.9996 ± .0001.
- Consistency of the EE spectra will be an important test.

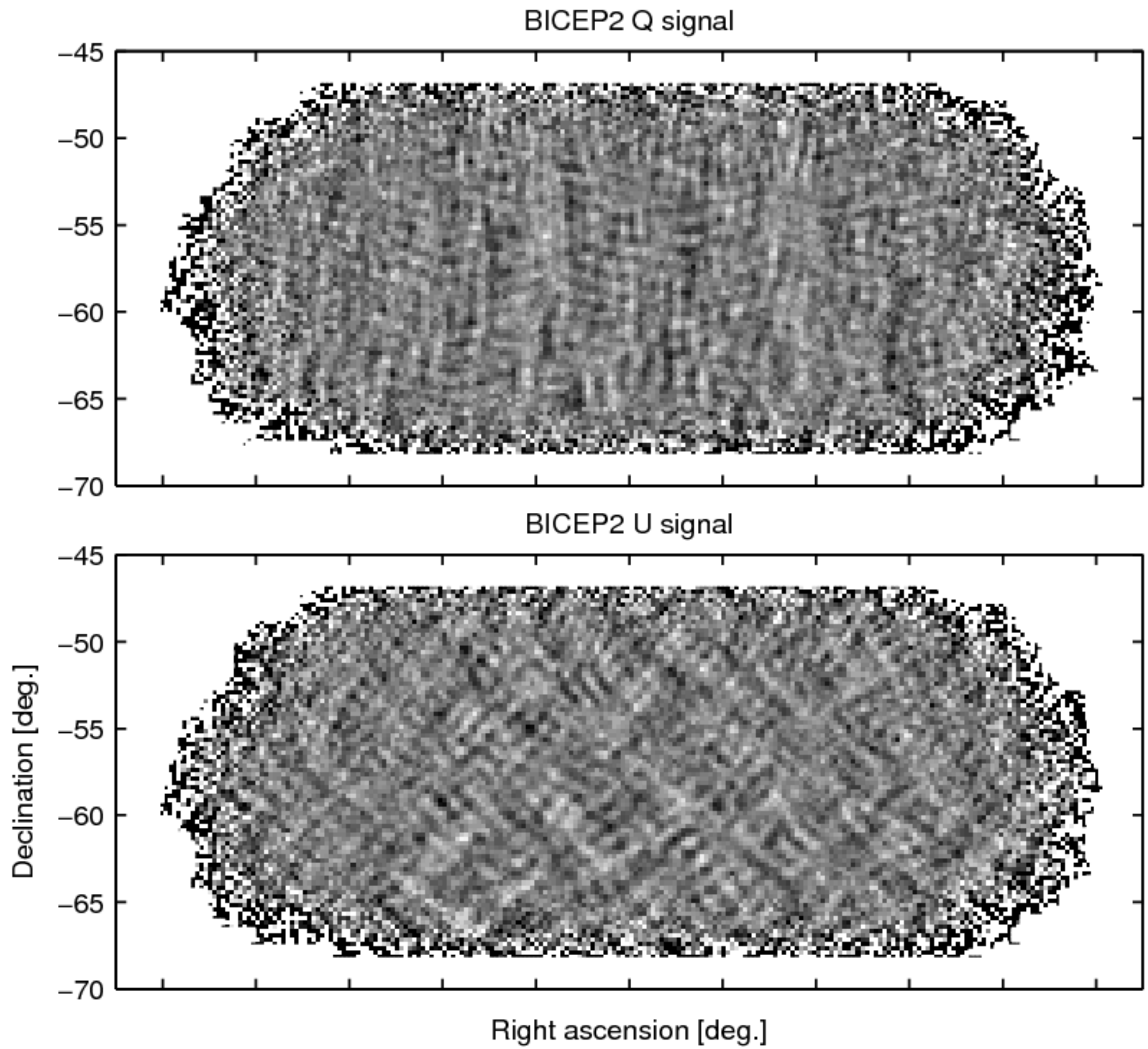
TT

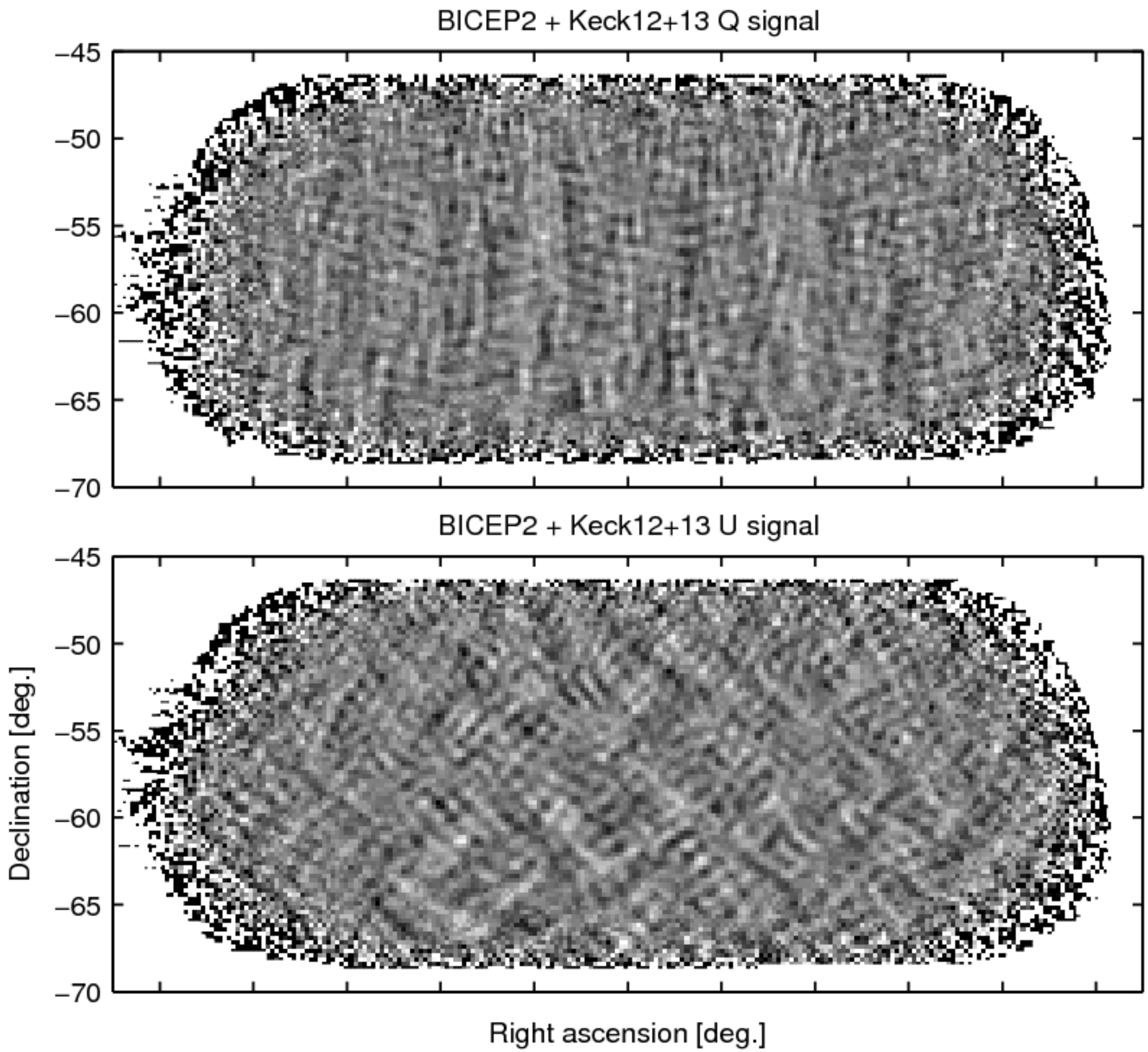


(error bars include no sample variance)



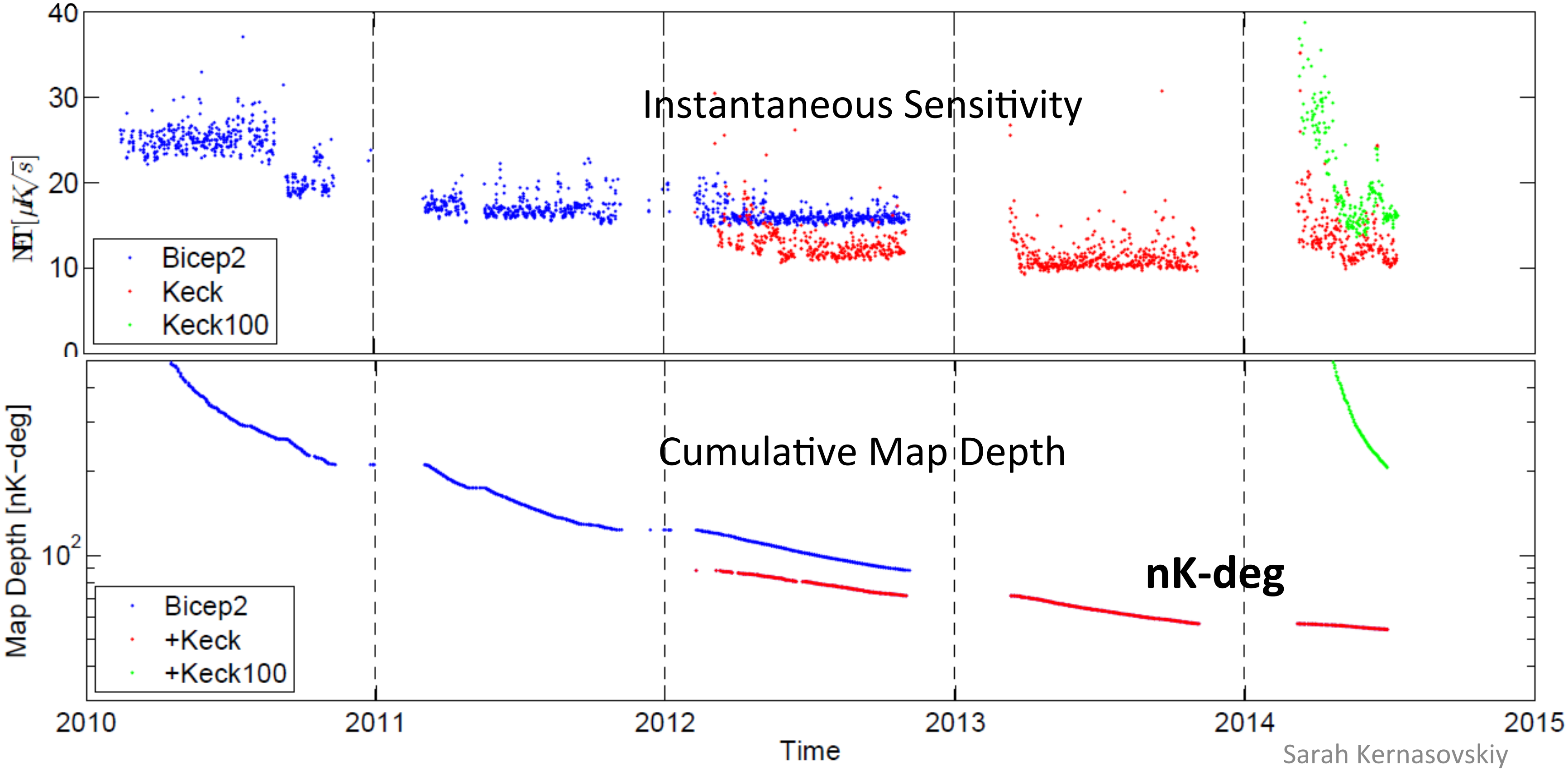
EE


BICEP2 Q signal
BICEP2 U signal
−45
−50
−55
−60
−65
−70
Declination [deg.]
Right ascension [deg.]

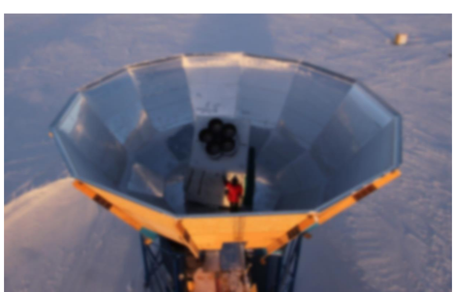

BICEP2 + Keck12+13 Q signal
BICEP2 + Keck12+13 U signal
−45
−50
−55
−60
−65
−70
Declination [deg.]
Right ascension [deg.]

Coming next (1): BICEP2 + Planck Joint analysis

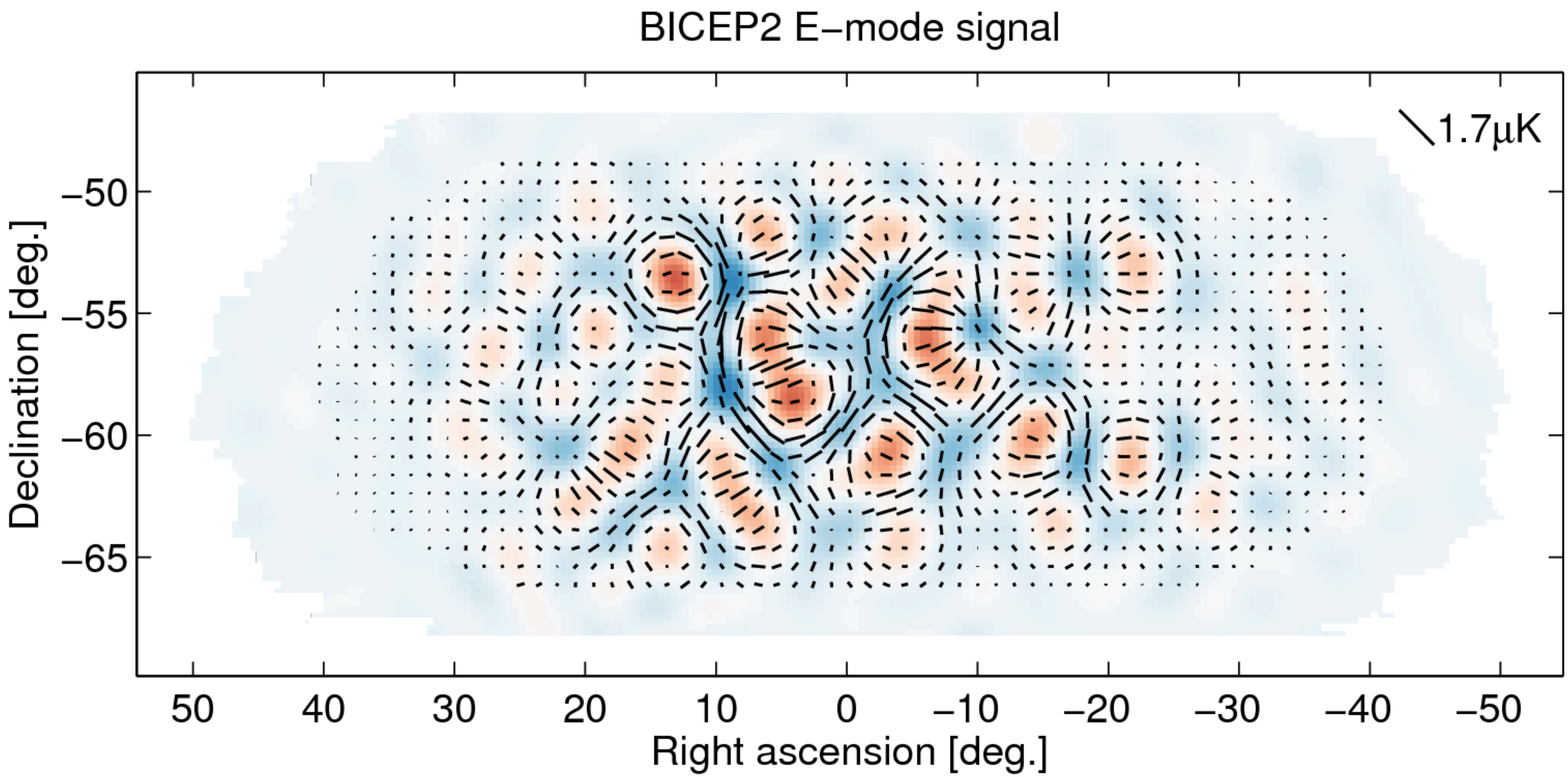
Coming next (2): Keck Array 2014 at 95 GHz



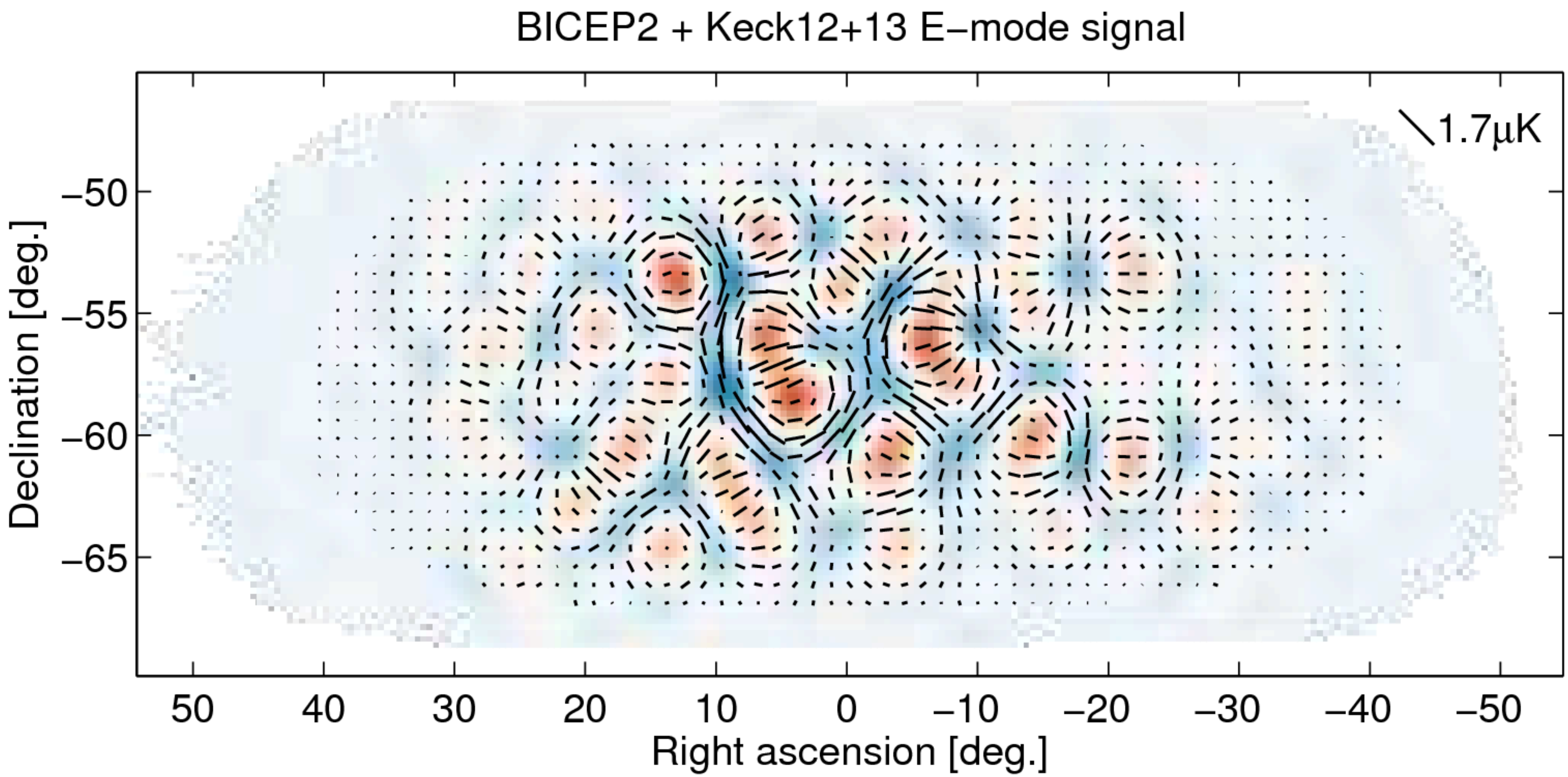
Sarah Kernasovskiy



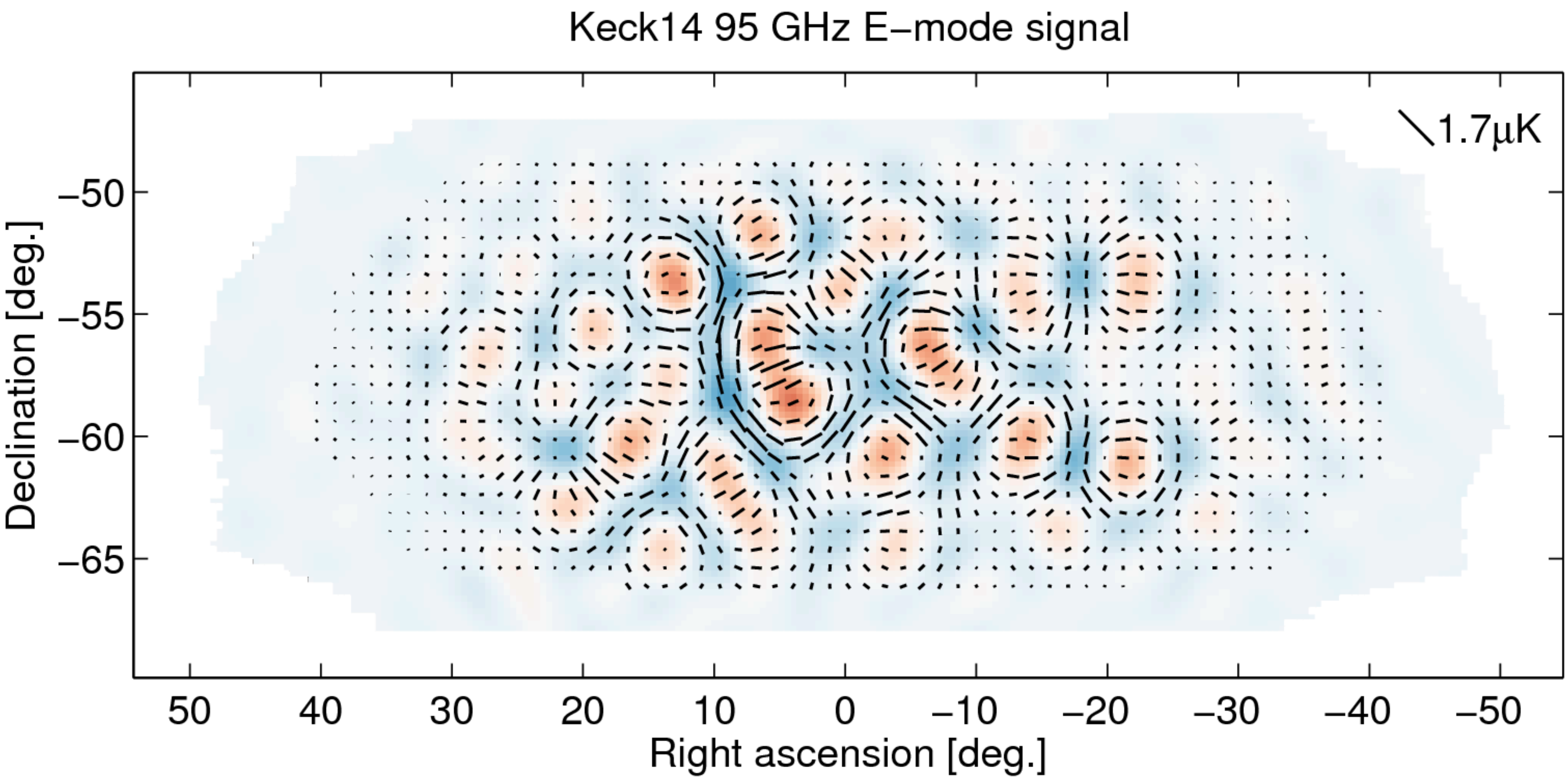
Keck 2014 has a full season with 2 receivers at 95 GHz



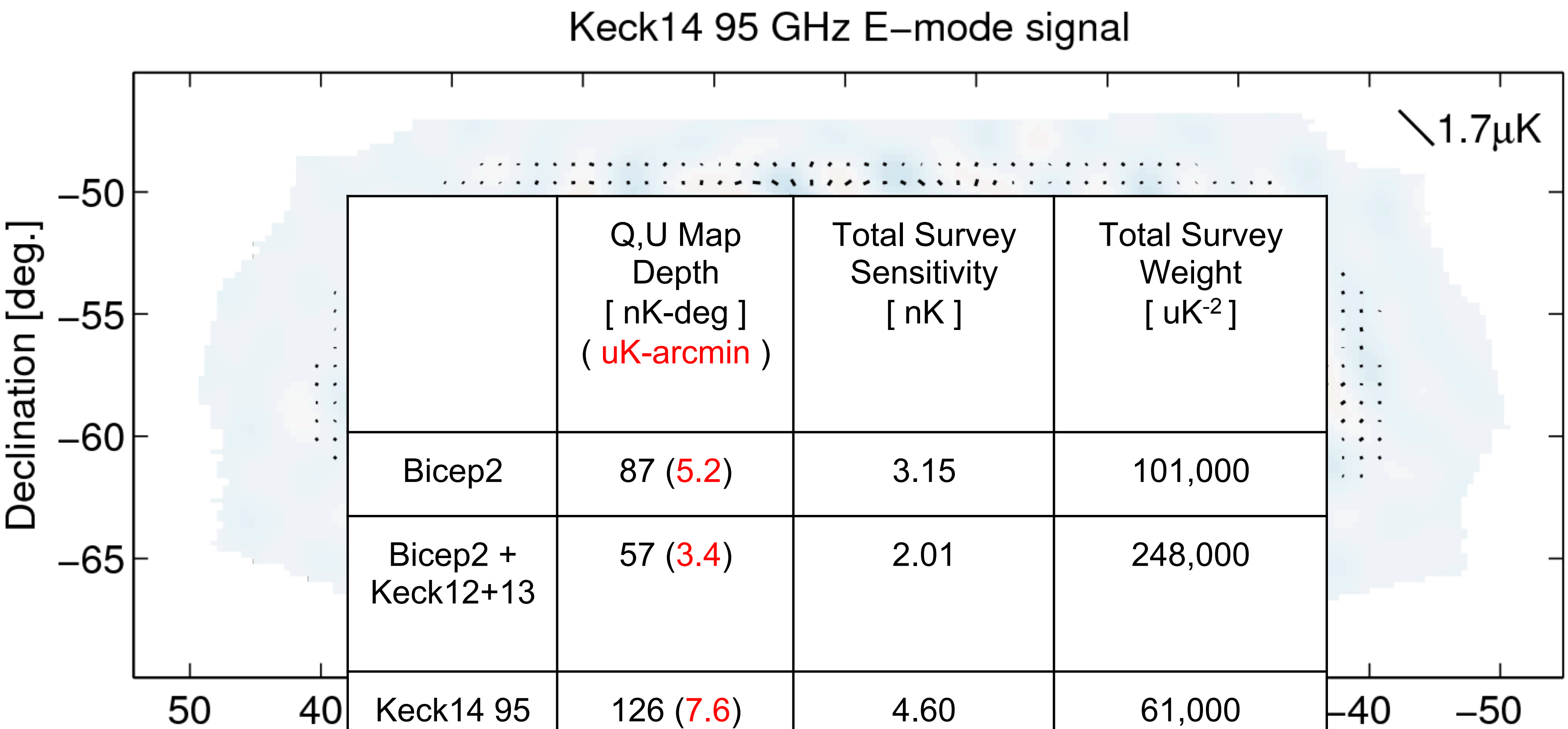
BICEP2 E−mode signal
1.7μK
−50
−55
−60
−65
Declination [deg.]
50
40
30
20
10
0
−10
−20
−30
−40
−50
Right ascension [deg.]


BICEP2 + Keck12+13 E−mode signal
1.7μK
Declination [deg.]
−50
−55
−60
−65
Right ascension [deg.]
50
40
30
20
10
0
−10
−20
−30
−40
−50

Coming next (2): Keck Array 2014 at 95 GHz



Coming next (2): Keck Array 2014 at 95 GHz

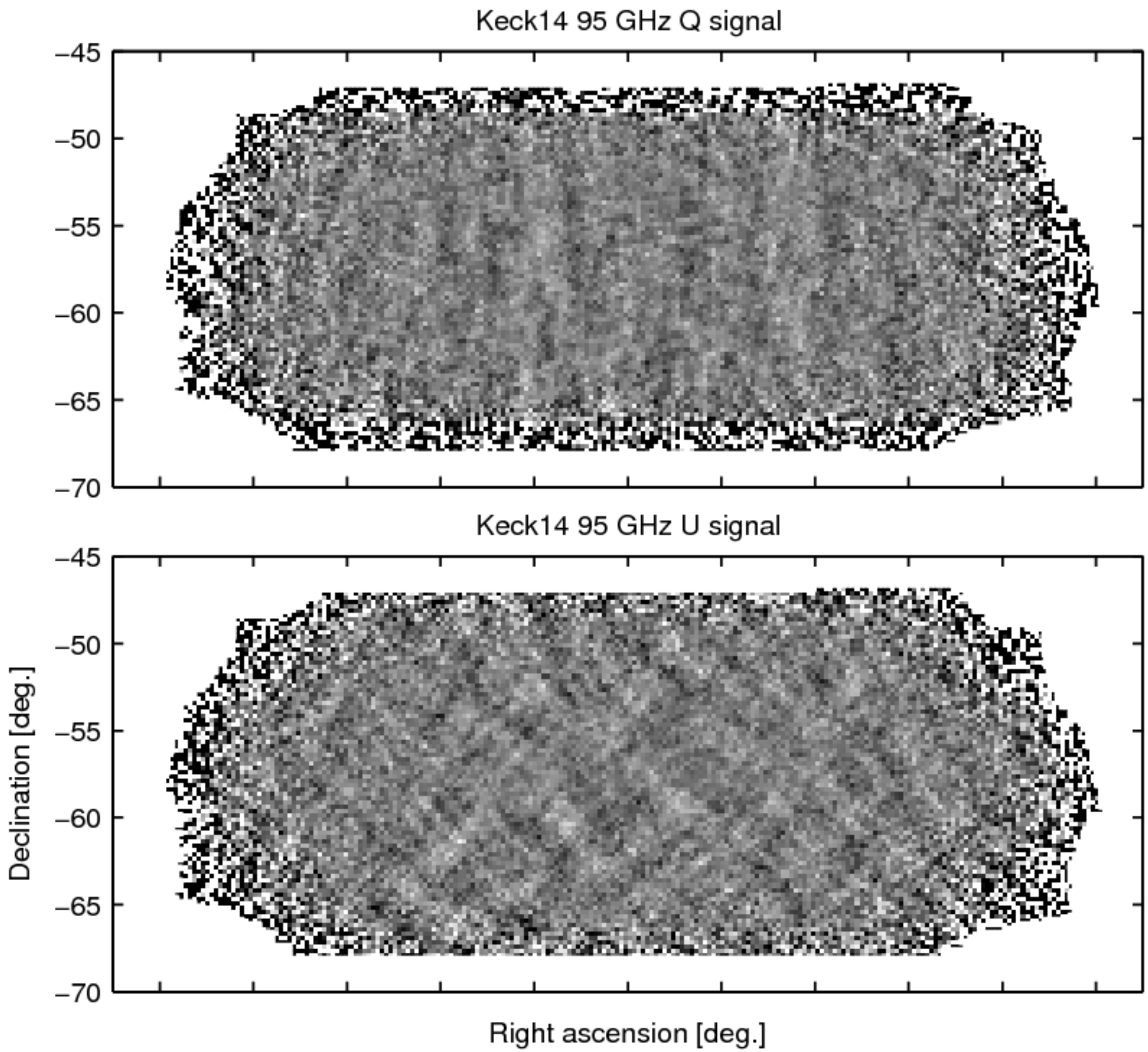


	Q,U Map Depth [nK-deg] (uK-arcmin)	Total Survey Sensitivity [nK]	Total Survey Weight [uK^{-2}]
Bicep2	87 (5.2)	3.15	101,000
Bicep2 + Keck12+13	57 (3.4)	2.01	248,000
Keck14 95 GHz	126 (7.6)	4.60	61,000

Dust BB expected ~5x fainter at 95 GHz vs 150 GHz

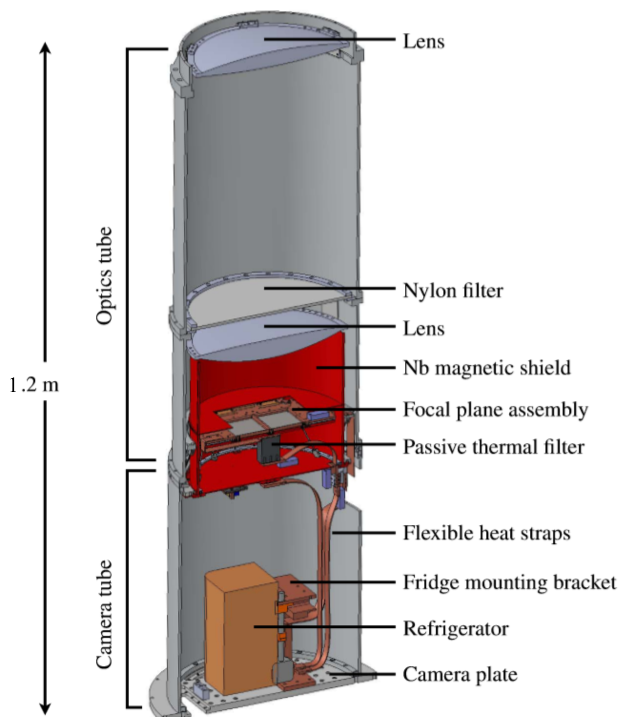
What's Next?

- We are actively working with the Planck collaboration on a joint analysis of the two data sets
  - The combination of the two is more powerful than either alone
  - Goal is a joint paper in late Nov (meeting here at UMN in a couple of weeks to discuss)
- We also ran two of the Keck Array receivers this season at 100 GHz
  - Data in the can probably offers a stronger constraint on the value of r than BICEP2+Planck
  - Guys here are gearing up to analyze as fast as possible when the data taking finishes on Nov 1 (Stefan, Eric, Justin)
- We are right now preparing to deploy BICEP3 which is an all 100GHz super receiver…


Keck14 95 GHz Q signal
Keck14 95 GHz U signal
−45
−50
−55
−60
−65
−70
Declination [deg.]
Right ascension [deg.]

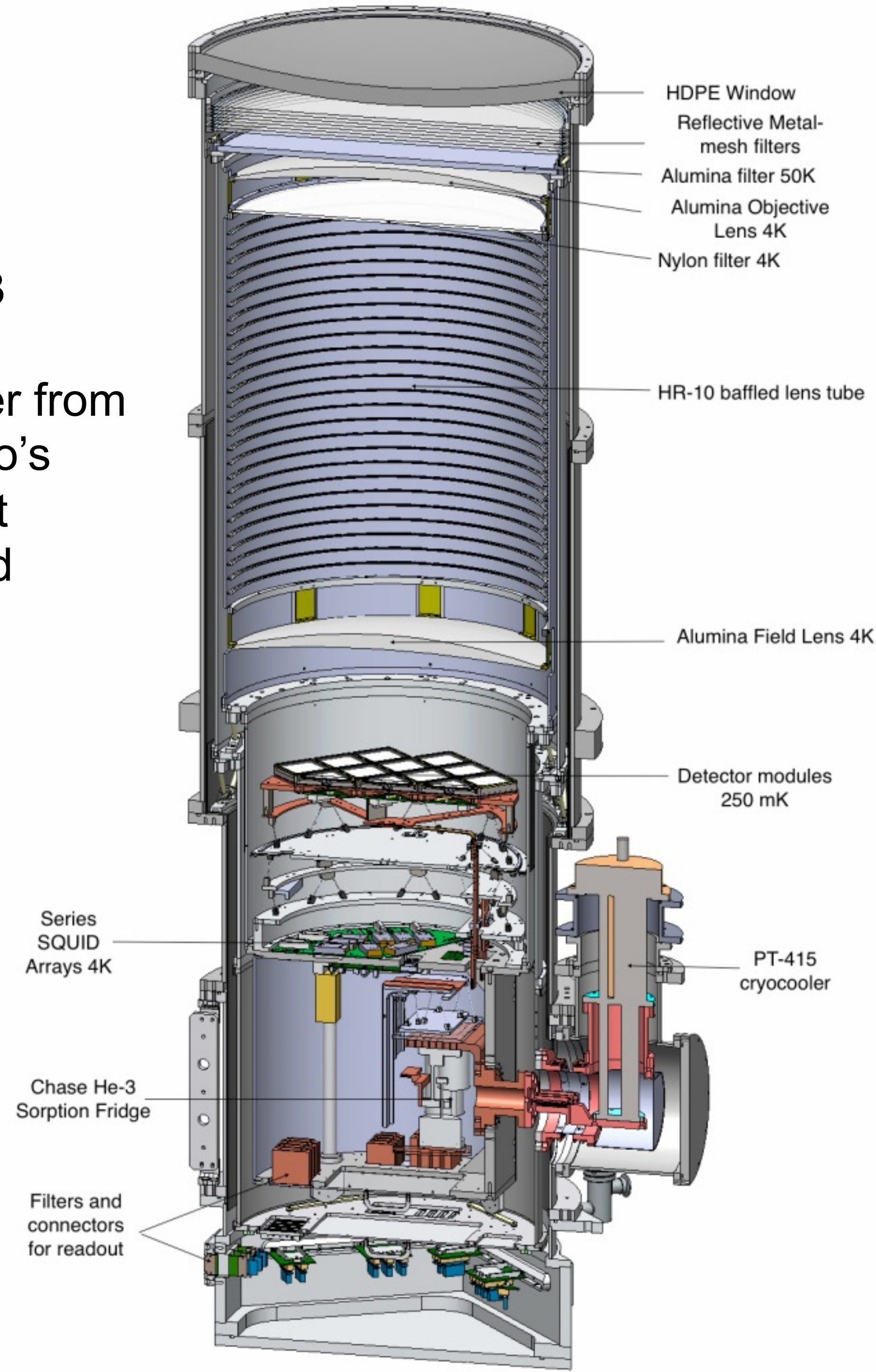
Coming next (3):
BICEP3 in 2015

BICEP2/Keck

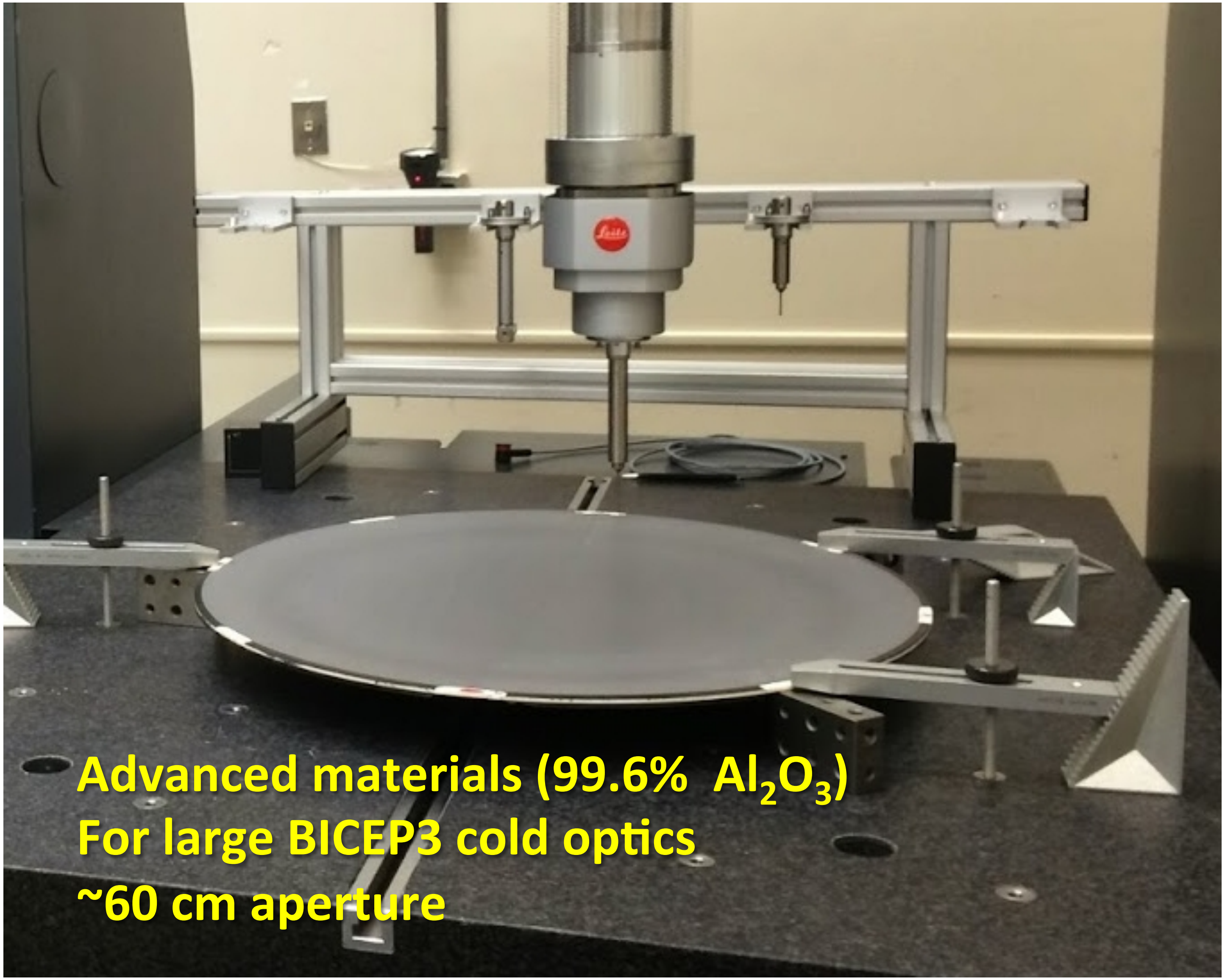


BICEP3

Receiver from C.L. Kuo's group at Stanford

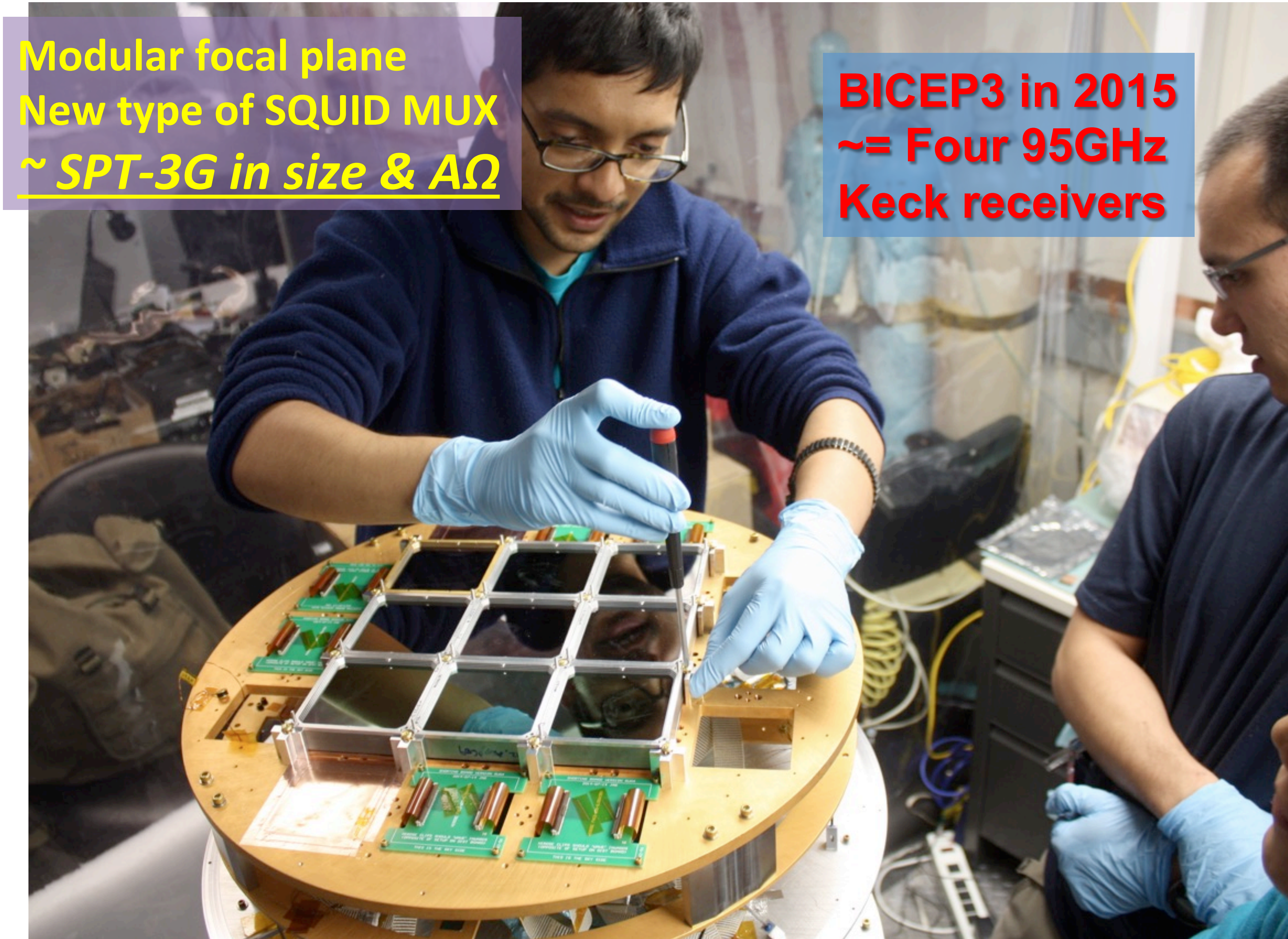


BICEP3 large optics



BICEP3 in lab: October 2014

BICEP3 at South Pole: December 2014



BICEP3 at South Pole: December 2014

Coming next (4): Keck Array 220 GHz

Keck receivers in 2015:
- 2 x 220 GHz
- 2 x 95 GHz
- 1 x 150 GHz

Keck first light @ 220 reported today (Jan 15)

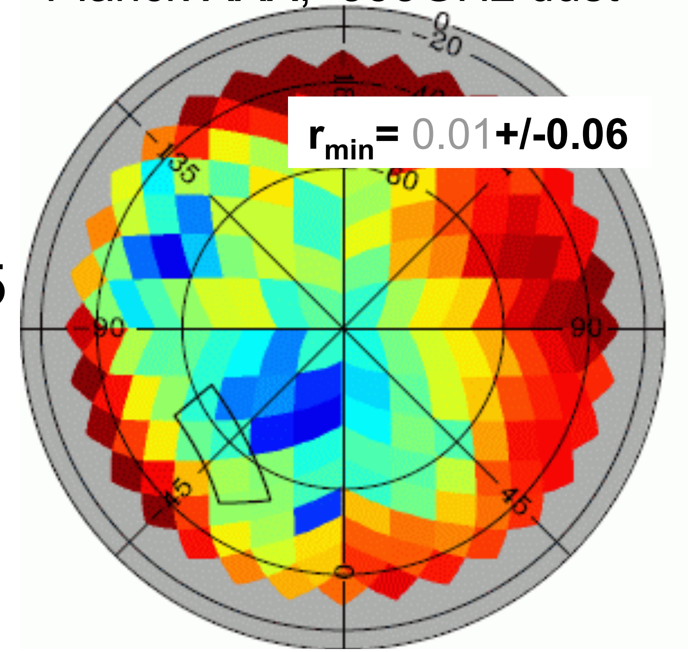
Coming next:

Results from current data:

- Planck X BK150 GHz ~ by end of Jan 2015
  - will be limited by noise on dust template over BK field
- Keck 95 GHz ~ by spring 2015
  - Maps are already nearly as deep as B2, 5x lower dust
- BICEP3 + Keck 220 GHz ~ by end of 2015
  - We've already added a 3rd frequency. Ultra-deep maps at 220 GHz coming, while 95 GHz will soon surpass 150 GHz. At this ultra-deep level, we can expect to learn a lot quickly about FG discrimination.
- More joint analyses to come: SPTpol, others soon?

Coming next:

Planck XXX, 353GHz dust



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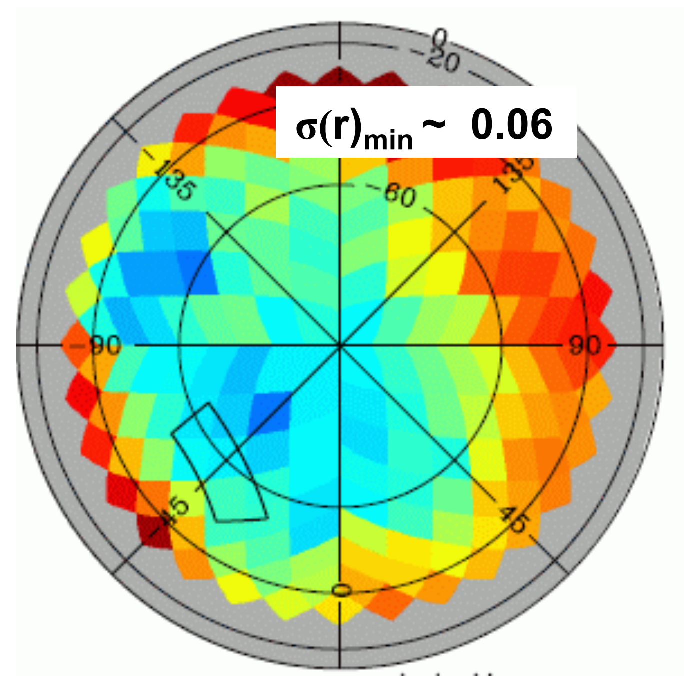

Prospects:

- More sky? Note that map at upper right is S/N < 1 everywhere cyan or bluer, with high correlations—so lots still to learn about the faintest regions. Looks promising for 95 GHz and larger f_sky.
- ***Small aperture measurements work very well, so expect another round of upgrade !***


Stay tuned !